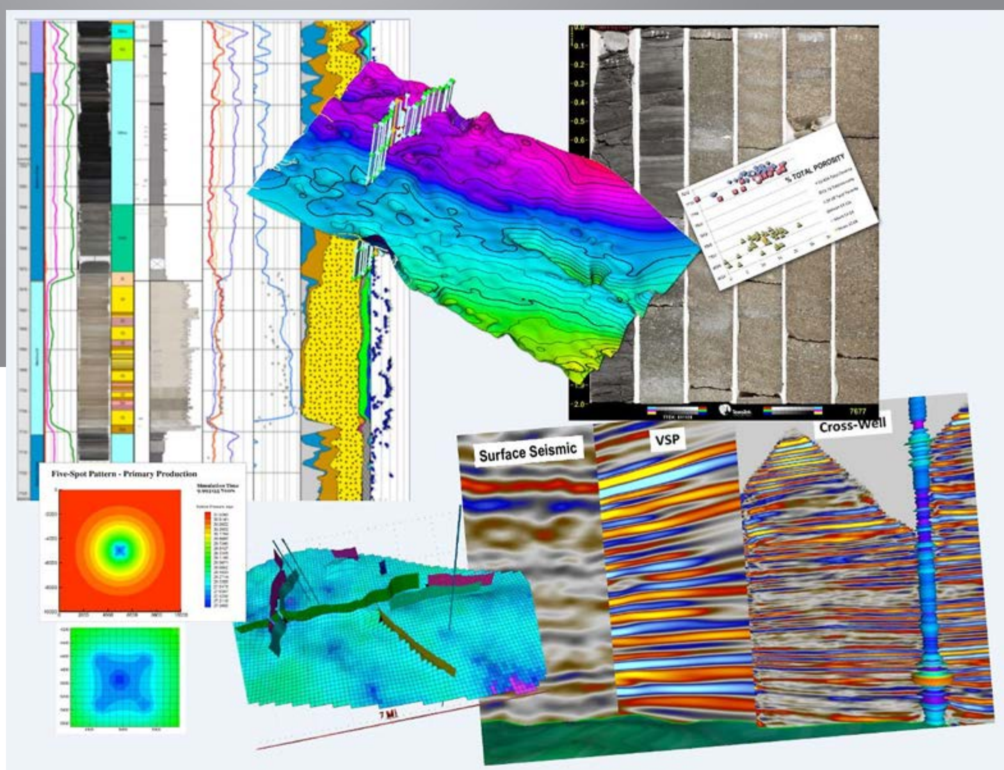
BEST PRACTICES:

Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects

2017 REVISED EDITION

DOE/NETL-2017/1844



NATIONAL ENERGY TECHNOLOGY LABORATORY

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June 2017

National Energy Technology Laboratory

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ACRONYMS AND ABBREVIATIONS

Acronym/ Abbreviation	Definition
2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
^{14}C	Radiogenic Carbon
AAPG	American Association of Petroleum Geologists
AoR	Area of Review
AZMI	Above-Zone Monitoring Interval
BHP	Bottom-Hole Pressure
BPM	Best Practice Manual
BSCSP	Big Sky Carbon Sequestration Partnership
CBL	Cement Bond Log
CBM	Coalbed Methane
CCS	Carbon Capture and Storage
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-SCREEN	CO_2 Storage Prospective Resource Estimation Excel Analysis
Corps	U.S. Army Corps of Engineers
CSLF	Carbon Sequestration Leadership Forum
CSRMS	Carbon Dioxide Storage Resource Management System
CWA	Clean Water Act
DAS	Distributed Acoustic Sensing
DOE	U.S. Department of Energy
DST	Drill Stem Test

Acronym/ Abbreviation	Definition
ECBM	Enhanced Coalbed Methane
ECOF	East Canton Oilfield
EDX	Energy Data eXchange™
EERC	Energy and Environmental Research Center
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
FE	Office of Fossil Energy
FEED	Front-End Engineering Design
FTP	File Transfer Protocol
FWU	Farnsworth Unit
GHG	Greenhouse Gas
GIS	Geographical Information System
GS	Geologic Storage
IBDP	Illinois Basin – Decatur Project
IZ	Injection Zone
km^2	Square Kilometer
m^2	Square Meter
MASIP	Maximum Allowable Surface Injection Pressure
MCOF	Morrow Consolidated Oilfield
mD	Millidarcies
MGSC	Midwest Geological Sequestration Consortium
MRCSP	Midwest Regional Carbon Sequestration Partnership
MVA	Monitoring, Verification, and Accounting

Acronym/ Abbreviation	Definition
N_2	Nitrogen
NATCARB	National Carbon Sequestration Database and Geographic Information System
NETL	National Energy Technology Laboratory
NEPA	National Environmental Policy Act
NRC	National Resource Council
O_2	Oxygen
ODNR	Ohio Department of Natural Resources
OOIP	Original Oil in Place
PCOR	Plains CO_2 Reduction Partnership
PHMSA	Pipeline and Hazardous Materials Safety Administration
PIIP	Petroleum Initially In Place
PNNL	Pacific Northwest National Laboratory
POGO	Production of Oil and Gas in Ohio Database
ppm	Parts per million
PRMS	Petroleum Resources Management System
PSI	Pounds per Square Inch
PTRC	Petroleum Technology Research Centre
QA	Quality Assurance
QC	Quality Control
RBDMS	Risk-Based Data Management System

Acronym/ Abbreviation	Definition
RCSP	Regional Carbon Sequestration Partnerships
ROW	Right-of-Way
RST	Reservoir Saturation Tool
SDWA	Safe Drinking Water Act
SECARB	Southeast Regional Carbon Sequestration Partnership
SEMs	Static Earth Models
SET	Spectra Energy Transmission
SP	Spontaneous Potential
SPE	Society of Petroleum Engineers
SPEE	Society of Petroleum Evaluation Engineers
SRO	Surface Read-Out
SWP	Southwest Regional Partnership on Carbon Sequestration
TDS	Total Dissolved Solids
TORIS	Tertiary Oil Recovery Information System Database
U.S.	United States
UIC	Underground Injection Control
UNEP	United Nations Environment Programme
USDW	Underground Source of Drinking Water
VOI	Value of Information
VSP	Vertical Seismic Profiling
WHP	Wellhead Pressure
WPC	World Petroleum Council

TERMINOLOGY

Caprock: A low-permeability sedimentary layer, which immediately overlies the reservoir and serves as a physical barrier to upward migration of CO_2 or brine from the top of the reservoir.

Confining Zone: One or more geologic barriers, typically low-permeability rock units that overlie or enclose a storage reservoir and are capable of preventing upward and/or lateral migration of CO_2 or brine out of the reservoir. A confining zone may contain multiple geologic seals.

Geologic Seal: A low-permeability sedimentary or structural unit, such as shale or a sealing fault, which provides a physical barrier to upward or lateral migration of CO_2 or brine out of the reservoir.

Injection Interval: The perforated interval, within an injection zone, through which CO_2 injectate is pumped into the storage reservoir.

Injection Zone: Specific sedimentary layers, within a storage reservoir, that are targeted for current or future CO_2 injection.

Potential Site: A specific project site that has potential capacity, injectivity, and containment for CO_2 storage but requires more data acquisition and further evaluation to be defined as Qualified Site.

Potential Sub-Region: A project region associated with a sub-regional trend of potential CO_2 storage sites, but which requires more data acquisition and/or evaluation to define Selected Areas.

Qualified Site: A project site that has met all required technical and non-technical criteria for CO_2 storage and is ready to permit.

Selected Area: A project area that shows sufficient capacity, injectivity, and containment for CO_2 storage but is currently poorly defined and requires more data acquisition and further evaluation to define Potential Sites.

Site Characterization: The process of evaluating Potential Sites to identify one or more Qualified Sites, which are viable for storage and ready to permit. Technical and non-technical data is used and data sampling/analysis is site-specific. Site Characterization involves two stages: (1) Initial Characterization involves analysis of available site-specific information and (2) Detailed Characterization involves site-specific field acquisition and analysis of new data.

Site Screening: The process of evaluating Sub-Regions within basins or other large geographic regions and identifying Selected Areas within those regions which warrant additional investigation for storage. Available technical and non-technical data is used and data sampling / analysis is coarse.

Site Selection: The process of evaluating Selected Areas and identifying Potential Sites within those areas, which warrant additional investigation for storage. Available technical and non-technical data are used, and data sampling/analysis is necessary and sufficient to identify individual sites.

Storage Complex: A geologic entity that is physically suitable for long-term storage of CO_2. It consists of: (1) one or more storage reservoirs, with permeability and porosity that allow injection and storage of CO_2; and (2) one or more low-permeability seals, which enclose the reservoir(s) and serve as barriers to migration of CO_2 out of the reservoir units.

Storage Formation: An established, named geologic formation that contains known or potential CO_2 storage reservoirs.

Storage Reservoir: Layers of porous and permeable rock, within a geologic formation, which are confined by impermeable rock, characterized by a single pressure system, and suitable for long-term storage of CO_2.

EXECUTIVE SUMMARY

Geologic Storage of anthropogenic carbon dioxide (CO_2) has gained recognition in recent years as a necessary technology approach for ensure environmental sustainability by reducing greenhouse gas emissions. The U.S. Department of Energy (DOE) Office of Fossil Energy's (FE) National Energy Technology Laboratory (NETL) are developing technologies that will enable widespread commercial deployment of geologic storage of CO_2 by 2025-2035.

DOE has engaged with technical experts in the Regional Carbon Sequestration Partnership (RCSP) Initiative to update its Best Practice Manuals (BPMs) for geologic storage projects. The BPMs are intended to disseminate knowledge gained through the RCSP Initiative and to establish uniform approaches for carrying out successful projects.

The first editions of the BPMs were completed between 2009 and 2013 and incorporated findings from RCSP Characterization Phase and small-scale Validation Phase field projects. The 2017 Revised Editions of the BPMs include lessons learned in more recent years, as the RCSPs have progressed to large-scale Development Phase field projects.

The five 2017 Revised Edition BPMs are:

- *BEST PRACTICES: Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects*
- *BEST PRACTICES: Public Outreach and Education for Geologic Storage Projects*
- *BEST PRACTICES: Risk Management and Simulation for Geologic Storage Projects*
- *BEST PRACTICES: Operations for Geologic Storage Projects*
- *BEST PRACTICES: Monitoring, Verification, and Accounting (MVA) for Geologic Storage Projects*

The BPMs are interconnected, and together they are intended to provide a holistic approach to carrying out a geologic storage project, from inception to completion.

The primary audience for this BPM is future storage project developers and CO_2 producers. It will also be useful for informing local, regional, state, and national governmental agencies. Finally, it will inform the general public about the rigorous analyses that are involved in screening, selecting, and characterizing potential geologic storage sites.

The process of identifying suitable sites with adequate storage involves methodical and careful analysis of the technical and non-technical features of promising areas. This BPM uses a CO_2 Storage Resource Classification System, which is modeled after the Petroleum Resources Management System (PRMS) as a framework for discussion of data to be collected, and analyses to be performed, for developing a site for geologic storage. The process, from initial exploration of large areas to site qualification, is divided into three stages: Site Screening, Site Selection, and Site Characterization. These stages correspond in rank order to three sub-classes within the Prospective Resources classification: Potential Sub-Regions, Selected Areas, and Qualified Site(s).

Project Definition is the important first step preceding Site Screening and is revisited at each subsequent stage in the development of a site. During Project Definition, the project developer establishes the scope and overall management plan for the project and establishes a set of criteria (including technical and economic criteria) that can be used to help guide subsequent stages.

Site Screening involves the evaluation of Potential Sub-Regions, within a larger area, such as a basin, to identify Selected Areas that are potentially suitable for geologic storage. The analysis in this step relies mostly on accessible data that can be obtained from public sources, though it may be necessary to acquire some additional data from private firms such as oil and gas, coal, mineral companies, or private vendors of related industry data.

During Site Selection, identified Selected Areas are evaluated using previous studies and additional, existing data to determine if a potential storage site can be identified. Technical information to be considered includes data from existing core samples, available seismic surveys, well logs, records and sample descriptions from existing or plugged/abandoned wells, and other available geologic data (some of which must be purchased). At the completion of this stage, the developer will have a list of the most promising Potential Sites to be evaluated during Site Characterization.

In the final step, Site Characterization, the project developer continues the evaluation of one or more of the higher-ranked Potential Sites. During this stage, a developer performs a detailed site-specific assessment of all geological, regulatory, site, and social issues for the designated Potential Sites, and either confirms or rejects a site as suitable for classification as a Qualified Site. While the analysis in Site Screening and Site Selection relies primarily on existing data, Site Characterization will likely involve the acquisition of new, site-specific data (e.g., seismic and well logging, core analysis, injectivity tests) and development of three-dimensional (3D) mathematical models of the selected injection and confining zone(s).

The CO_2 Storage Resource Classification System is project-based, wherein each project is classified according to its maturity status (broadly corresponding to its chance of commerciality) using three main classes: Prospective Storage Resources, Contingent Storage Resources, and Storage Capacity. This BPM provides guidelines on investigations that are associated with the Prospective Storage Resource class. Once a project has been classified as a Qualified Site, at the end of Site Characterization, it moves from the Prospective Storage Resource class to Contingent Storage Resource class. Guidelines for investigations that support the development of a storage site as it advances from a Contingent Storage Resource to Storage Capacity are found in the “Operating Carbon Dioxide Storage Projects in Deep Geologic Formations” BPM (NETL, 2016a).

Finally, this BPM is a revision to the 2013 edition. In addition to updating the contents to reflect the current state-of-knowledge and extensive experiences of the RCSPs, it is also an enhancement because it contains lessons learned and case studies that are specific to the RCSPs and provide guidelines for Project Definition, Site Screening, Site selection, and Site Characterization.

1.0 INTRODUCTION

Geologic Storage of anthropogenic carbon dioxide (CO_2) has gained recognition in recent years as a necessary technology approach for ensure environmental sustainability by reducing greenhouse gas emissions. The U.S. Department of Energy (DOE) Office of Fossil Energy's (FE) National Energy Technology Laboratory (NETL) are developing technologies that will enable widespread commercial deployment of geologic storage of CO_2 by 2025-2035.

As an important step in meeting this objective, DOE/FE/NETL established the Regional Carbon Sequestration Partnership (RCSP) Initiative (see Appendix I). This national Initiative, launched in 2003, includes seven regional partnerships tasked with developing and testing technologies and approaches for safe and permanent storage of CO_2 in different geologic and geographic settings across the United States. An important outcome of the RCSP Initiative is the publication of a series of topical BPMs for geologic storage projects. The BPMs are intended to disseminate knowledge gained through the RCSP field efforts and to establish effective methods, reliable approaches, and consistent standards for carrying out successful geologic storage projects.

The first editions of the BPMs were completed between 2009 and 2013 and presented salient findings of the RCSPs' Characterization and Validation Phase field projects. Since that time, the RCSPs have progressed to large-scale Development Phase field projects. For the 2017 Revised Editions of the BPMs, DOE/FE/NETL has worked closely with technical experts from the RCSPs to incorporate new findings and lessons learned from these Development Phase projects.

The five 2017 Revised Edition BPMs are:

- *BEST PRACTICES: Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects*
- *BEST PRACTICES: Public Outreach and Education for Geologic Storage Projects*
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Taken separately, each BPM can serve as a stand-alone guide for conducting specific activities related to Characterization, Public Outreach, Risk Management, Operations, or MVA. Taken together, the five BPMs are interconnected—each linked to the others by the interdisciplinary nature of a geologic storage project. They are intended to provide a holistic approach for carrying out a geologic storage project, from inception to completion.

The 2017 Revised Edition BPM on "Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects" is a revision of an earlier version, published in 2010.

This manual is process-based and provides best practice guidelines for locating and developing a geologic storage project from the initial stages of regional exploration, at the basin-scale, to the point where a site can be considered qualified for significant additional development investment for commercial storage. Throughout the manual, examples and lessons learned are provided as "case studies" from the RCSP Large-Scale Development Phase field projects. Figure 1.1 and Table 1.1 provide the fundamental information on these RCSP projects, including project name, project type, geologic basin, amount of stored CO_2, and geographic location. Some additional context for the RCSP Development Phase field projects is provided in Appendix I.

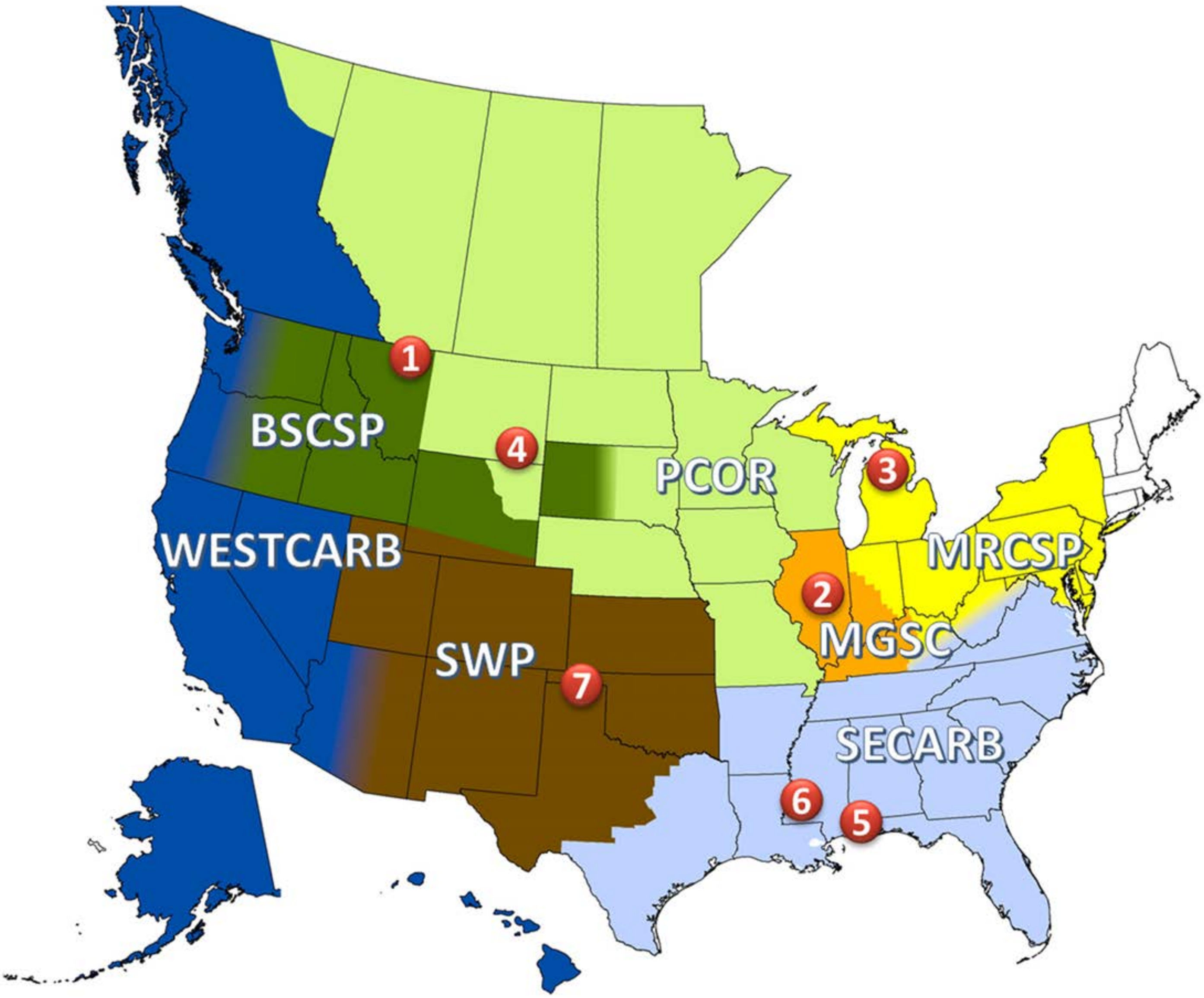

Figure 1.1: Locations of RCSP Large-Scale Development Phase Projects.

(Numbers correspond to Table 1.1)

Table 1.1: RCSP Large-Scale Development Phase Projects.

(See Figure 1.1 for project locations)

RCSP Development Phase Projects				
Number on Map	**Project Name**	**Project Type**	**Geologic Basin**	**Metric Tons of CO_2 Stored**
1	**Big Sky Carbon Sequestration Partnership–Kevin Dome Project**	Saline Storage	Kevin Dome	N/A (no injection date)
2	**Midwest Geological Sequestration Consortium–Illinois Basin Decatur Project**	Saline Storage	Illinois Basin	999,215 (final stored, and project in post-injection monitoring phase)
3	**Midwest Regional Carbon Sequestration Partnership–Michigan Basin Project**	Enhanced Oil Recovery	Michigan Basin	596,282 (as of Sept. 30, 2016)
4	**The Plains CO_2 Reduction Partnership–Bell Creek Field Project**	Enhanced Oil Recovery	Powder River Basin	2,982,000 (final stored, and project in post-injection monitoring phase)
5	**Southeast Regional Carbon Sequestration Partnership–Citronelle Project**	Saline Storage	Interior Salt Basin, Gulf Coast Region	114,104 (final stored, and project in post-injection monitoring phase)
6	**Southeast Regional Carbon Sequestration Partnership–Cranfield Project**	Saline Storage	Interior Salt Basin, Gulf Coast Region	4,743,898 (final stored, and project in post-injection monitoring phase)
7	**Southwest Carbon Sequestration Partnership–Farnsworth Unit Project**	Enhanced Oil Recovery	Anadarko Basin	490,720 (as of Sept. 30, 2016)

Steps in the Process

The first step is Project Definition (Chapter 2), which should be conducted prior to beginning exploration activities to establish an initial plan for overall project management and a detailed plan for subsequent stages, including contingencies. As part of project definition, the developer establishes a set of technical and economic criteria that can be used to help rank potential candidates identified at different stages in site development.

Following project definition, the stages in site development are organized around decision points related to narrowing the scale of investigation from very large regional assessments down to specific sites that might be developed for commercial storage. Figure 1.2 illustrates the relationship between the scale of investigation and the major steps in the process of finding and developing Qualified Sites. Site Screening (Chapter 3) provides guidelines for large-scale investigations focused on regions, called Potential Sub-Regions, to determine a list of prospective areas, called Selected Areas, within those regions. Site Selection (Chapter 4) provides guidelines for investigation of the Selected Areas to determine a list of sites, called Potential Sites, that are worthy of additional site-specific investigations. Site Characterization (Chapter 5) provides guidelines for site-specific investigation, and possible investment in new data, to determine which Potential Sites might be considered to be Qualified Sites for commercial investment. This BPM provides guidance on characterization of the geology of sites. But, it goes beyond geology to provide a guide for considering the broader set of factors that determine the commerciality of a potential carbon dioxide (CO_2) geologic storage site.

Finding and Developing Qualified Sites

Each stage in the site development and evaluation process is subdivided into components and accompanying analyses. Each of the components contains several elements to consider during the analyses. Each stage builds on the previous one, paring down a large region into a select few sites based on identified component evaluations. It is a process that is designed to:

- Establish that the site has the resources to accept and safely store the anticipated quantity of CO_2 at the desired injection rate for the storage project
- Provide input data to models required to predict site performance in terms of pressure change and CO_2 plume evolution
- Minimize the probability of adverse effects on the environment
- Identify and address any potential regulatory, subsurface ownership, site access, and pipeline issues
- Ensure the site has the capability to meet the performance standards established for the project, such as operational efficiency, reliability, and safety
- Ensure alignment of national, regional, and local social, economic, and environmental interests

The manual is written with an eye to the future, when carbon capture and storage (CCS) becomes commercial, and subsurface storage space will be considered a resource. Given the many similarities, both technical and non-technical, between exploration and production of hydrocarbons and exploration and storage of CO_2, it is plausible to suggest that there would be similarities in approaches to resource management. An important assumption underlying the structure of the BPM is that the steps taken in development of commercial CCS projects, and the process by which the maturity (readiness for commercial injection) of a project is

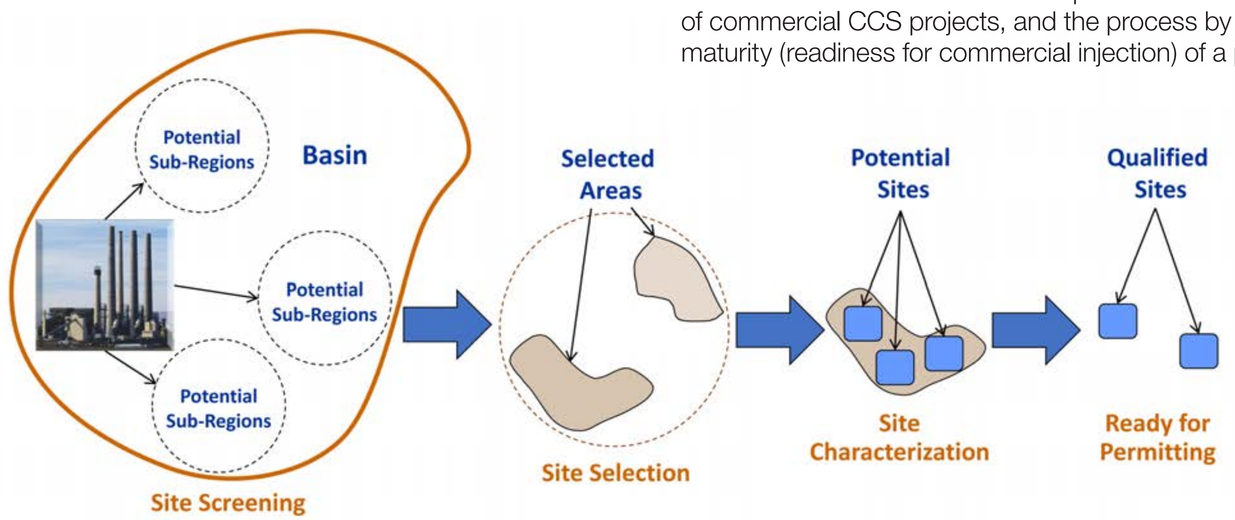

Figure 1.2: Illustration of the Relationship Between Scale of Investigation and Major Steps in Process of Finding and Developing Qualified Sites

judged, will be analogous to how the petroleum industry develops projects and assesses project maturity. Thus, the guidelines for finding and developing a geologic storage site are presented within the framework of the CO_2 Storage Resource Classification System, which is modeled after the Petroleum Resources Management System (PRMS).

The CO_2 Storage Resource Classification System is project-based, wherein each project is classified according to its maturity status (broadly corresponding to its chance of commerciality) using three main classes: Prospective Storage Resources, Contingent Storage Resources, and Storage Capacity. The analogous classes in the PRMS are Prospective Resources, Contingent Resources, and Reserves. The boundaries between different levels of project maturity may be referred to as decision gates. The CO_2 Storage Resource Classification System is illustrated in Figure 1.3 and discussed in detail in Chapter 6. It was originally proposed in the first edition of this BPM (published in 2010), and slightly revised in this edition.

There are sub-classes within each of the major classes in the CO_2 Storage Resource Classification System. As shown in Figure 1.3, the sub-classes within Prospective Storage Resources are: Potential Sub-Regions, Selected Areas, and Qualified Site(s). The evaluation processes associated with each of these sub-classes are, respectively: Site Screening, Site Selection, and Site Characterization. They correspond to the scale and level of detail in the different stages of development of a site. This BPM provides guidelines for investigations associated with the Prospective Storage Resource class. After a project site has been Qualified, at the end of Site Characterization, the project moves from the Prospective Storage Resource to Contingent Storage Resource. Guidelines for site development investigations associated with Contingent Storage Resources and Storage Capacity classes are presented in the "Operating Carbon Dioxide Storage Projects in Deep Geologic Formations" BPM (NETL 2016a).

Petroleum Industry	CO_2 Geological Storage
Reserves	**Storage Capacity**
On Production	Active Injection
Approved for Development	Approved for Development
Justified for Development	Justified for Development
Contingent Resources	**Contingent Storage Resources**
Development Pending	Development Pending
Development Unclarified or On Hold	Development Unclarified or On Hold
Development Not Viable	Development Not Viable
Prospective Resources	**Prospective Storage Resources**
Prospect	Qualified Site(s)
Lead	Selected Areas
Play	Potential Sub-Regions

Prospective Storage Resources	
Project Sub-Class	**Evaluation Process**
Qualified Site(s)	Site Characterization
Selected Areas	Site Selection
Potential Sub-Regions	Site Screening

Figure 1.3: Comparison of Petroleum Industry Classification and CO_2 Storage Resource Classification

Adapted from SPE/WPC/AAPG/SPEE Resource Classification System.
(© 2007 Society of Petroleum Engineers, Petroleum Resources Management System)
(Note: this table should be read from the bottom to top)

2.0 PROJECT DEFINITION AND MANAGEMENT

Planning and managing a project from Site Screening through Site Characterization is critical to successfully maturing a potential storage site. Prior to initiating any evaluations, an analysis of a project's needs, organization, management structure, and resources should be conducted for the entire characterization process. Understanding that project needs will evolve as the project matures, the project developer should create an initial plan and a framework for addressing future contingencies. The initial plan should be revisited at each stage to better manage the project's needs.

2.1 PROJECT ANALYSIS

Prior to any technical evaluation performed during Project Definition, the developer should execute a project analysis consisting of at least six elements: (i) Scope, (ii) CO_2 Strategy, (iii) Evaluation Criteria, (iv) Resources, (v) Schedule, and (vi) Risk Assessment. These analyses will be revisited at the beginning of each stage of the development of a site and referred to as Project Management. The process flowchart for Project Definition is shown in Figure 2.1 and guidelines are summarized in Table 2.1.

Table 2.1: Guidelines for Project Definition

PROJECT DEFINITION/MANAGEMENT	Project Analysis	Scope	Define overall project and describe processes for Site Screening, Site Selection, and Site Characterization. Identify project objectives and criteria to evaluate project success or failure.
		CO_2 Strategy	Develop a CO_2 management strategy that identifies CO_2 sources, volumes, rates of delivery, and target injection rates. Assess feasibility of several implementation options, with associated risks and mitigation options.
		Evaluation Criteria	Establish criteria to be used for qualifying and ranking sites during Site Screening, Site Selection, and Site Characterization. Criteria should include technical, economic, and social parameters.
		Resources	Identify personnel, equipment, and funding resources necessary to complete Site Screening, Site Selection, and Site Characterization processes. Identify necessary areas of expertise, financial thresholds, potential contingencies, and other resource risks.
		Schedule	Develop realistic project schedule for Site Screening, Site Selection, and Site Characterization. Include milestones and contingency plans to mitigate schedule delays.
		Risk Assessment	Conduct risk assessment to identify scenarios that could prevent the project from achieving commerciality. Define mitigation options, and develop implementation plan with go/no-go decision gates.

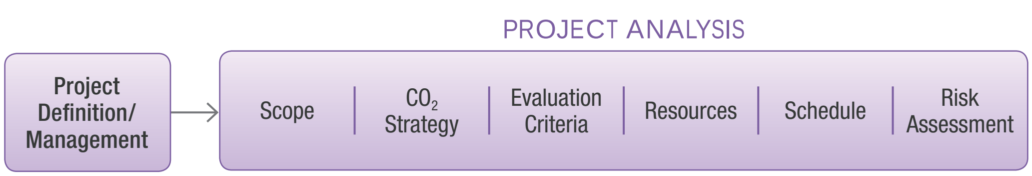

Figure 2.1: Process Flowchart for Project Definition

2.1.1 PROJECT SCOPE

The project scope addresses all stages of the site evaluation process, from Site Screening through Site Characterization and should anticipate increasing costs as the level of detail increases throughout the three stages of evaluation. The plan should focus on understanding and reducing the uncertainties that could arise as the project matures, including issues related to geology, community, modeling, or the surface site. If multiple sites are to be developed, a project scoping exercise is needed for each. The Project Definition plan should be dynamic and, at this initial stage, provide a baseline from which adjustments can be made as the project matures and circumstances change. Failure to scope each aspect of the project correctly could result in unforeseen delays and potential cost overruns that could lead to failure of the project.

2.1.2 CO_2 MANAGEMENT STRATEGY

A CO_2 management strategy should be developed that considers CO_2-related issues, including: the planned source or sources of CO_2 intended for injection; maximum and minimum volumes of CO_2 over project lifetimes; the number of injection sites that might be required; the potential need for backup capacity; pressure of CO_2 throughout the systems; planned years of operation; and the chemical properties of the potential CO_2 gas stream. Delivery system options, such as the existence of pipeline infrastructure, should also be considered.

The CO_2 management strategy is used to inform the evaluation criteria discussed in the next section. For example, the CO_2 management strategy will have a bearing on determining if the injectivity and storage volume is sufficient to advance a project to the next stage of site evaluation.

A case study (Case Study 2.1) from the SWP Farnsworth Unit Project illustrates the importance of an assured CO_2 supply. A variable supply may cause interruptions in storage operations, which will have direct impacts on project cost and project management.

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2.1.3 EVALUATION CRITERIA

Site Screening results in a list of Selected Areas that must be ranked. As part of Project Definition, developers should establish criteria for ranking that considers factors that could lead to a go/no-go decision for moving to the next stage in the site evaluation process, or lead to a contingent set of analyses within the current stage.

Primary factors that may lead to go/no-go decisions include:

- The site can be permitted under all relevant Federal, state, and local regulations
- Requirements can be met for project sites that are proximal to, or contain, protected and sensitive areas such as cultural resources, wetlands, etc.
- Mechanisms for obtaining access from surface and subsurface owners for storage, surface facilities, and pipelines can be established
- Risk assessment (including a wide variety of factors such as financial, public acceptance, political, technical, various types of liability, uncertainties, etc.), management, and mitigation options are acceptable to the project development team
- Ability to conduct expected or required monitoring is assured
- Costs including all of the above elements are within project budget

Additional factors to be taken into consideration include:

- Prospective Storage—does the evaluated site have sufficient storage for the planned volume of CO_2, or would multiple sites and/or multiple wells need to be developed?
- Rock Facies—in the case of a large saline formation, is there a single facies within a continuous vertical column of connected flow units, or does a series of stacked or amalgamated depositional compartments exist that may or may not be in flow communication?

- Structural Setting—are there potential faults that compartmentalize the injection zone or create closed or partly closed flow boundaries?
- Pipeline Issues—does one site require fewer miles of pipeline or have less rugged terrain for pipeline installation?

Not all factors are relevant to every site, so each project will likely establish its own set of ranking criteria.

Case Study 2.2, also from the SWP Farnsworth Unit Project, illustrates the importance of having a pipeline or other means of transporting CO_2 to the site under consideration.

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Developers should also consider explicitly ranking risk factors. Some teams will highly rank one set of risks, while others will be more concerned about another set leading to different Site Selection approaches. For example, one developer might rank protected areas highly, leading to siting preferences such as extensive buffer zones around parks. Another team might rank risks of poor injectivity higher, leading to a preference for projects that could demonstrate high injectivity.

2.1.4 RESOURCES

Project Definition activities identify and plan for resource needs, especially the skilled personnel and funding necessary to complete all stages in the site evaluation process and for the entire project. Cross-functional teams consisting of appropriate skillsets should be created for each stage in the evaluation process (at various points this will include geoscientists, engineers, modeling experts, and individuals with business, legal, social characterization, regulatory, and environmental expertise). It is important to create a project management hierarchy and management communications network to ensure that each person understands his or her role in the project and that there is clear communication of the project goals, data, and findings.

Adequate funding is essential. Therefore, a funding-needs analysis should be completed for each component within each stage of the site evaluation process. A number of decision points may require repetition of a just-completed analysis or unavoidable delays may be encountered. As is usually found in any major project, for planning purposes, contingency funding may be needed and should be identified.

2.1.5 SCHEDULE

Based on an assessment of planned activities and available resources, the Project Definition should include a realistic schedule that includes the time requirements to fully complete each evaluation component. As with the funding assessment, tasks may need to be repeated or requirements for unanticipated data collection, analysis, and modeling may alter a project's schedule. Contingency timing should be allotted for repeating analyses of more than one region, area, or site in the initial project schedule.

2.1.6 RISK ASSESSMENT

The final element in Project Definition is a risk assessment that identifies potential project risks and a corresponding (tailored) mitigation plan. Further information on the theory and application of risk assessment to geologic storage is found in the "Risk Management and Simulation for Geologic Storage of CO_2" BPM (NETL, 2016b). Project risks are different from those included in a regulatory analysis because they include events or circumstances that could result in a project not maturing to the status of Contingent Storage Resource and potentially on to commercially available Storage Capacity. The following are a few potential project risks: the CO_2 source or pipeline does not develop as planned; a selected reservoir is technically or economically unsuitable; mechanical failures in equipment occur; sufficient pore space or surface rights are not secured; significant public opposition is encountered; and legal and regulatory regimes change as they become more defined. The initial risk assessment during Project Definition must ascertain, with a high degree of confidence, that the initial project plan is capable of evaluating each of the defined elements in sufficient depth to allow proper technical and economic decisions to be made and public confidence is established. The risk assessment and associated mitigation plans must confirm that the project's scope, staffing and competence levels, funding levels, schedule, and criteria are sufficient to accomplish the required evaluations.

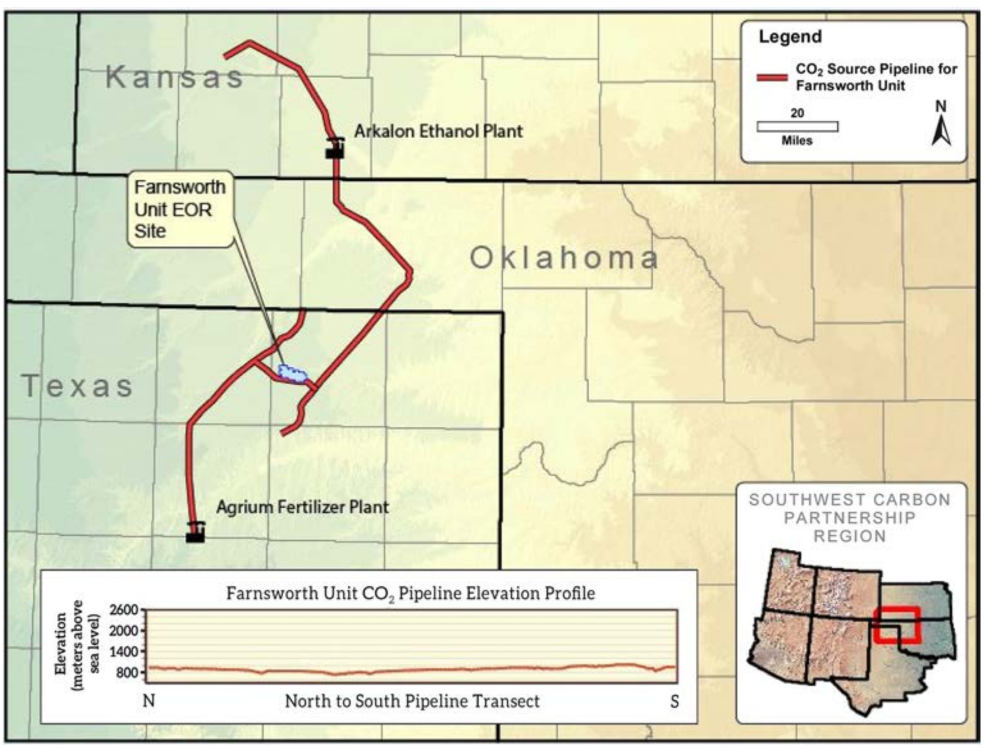
2.2 RCSP CASE STUDIES

CASE STUDY 2.1 — SWP

SOUTHWEST REGIONAL PARTNERSHIP ON CARBON SEQUESTRATION (SWP)

Considerations of Reliability of CO_2 Supply and its Interdependence with Other Economic Factors

The CO_2 supply for storage operations is much more important than the public may realize. For example shutdown and restart of injection facilities can incur a tremendous cost. At the Farnsworth Unit (FWU) CO_2-enhanced oil recovery (EOR) field injection and storage operation (SWP Farnsworth Unit Project), two anthropogenic sources, including an ethanol plant in Kansas and a fertilizer plant in Texas, send CO_2 to injection facilities via pipeline. Both sources are roughly equidistant from the field (see figure below). The ethanol plant is subject to the cost of oil in many ways. If oil and gasoline prices are relatively high, the cost of ethanol is more attractive at market, and thus production will likely be greater. In contrast, when gas prices are relatively low, ethanol demand will decrease resulting in lower production and CO_2 emissions at the ethanol plant. Additionally, ethanol production is subsidized by Federal funds, and such subsidies are subject to change, implying that associated CO_2 emissions rates may change as well. For the fertilizer plant, natural gas is a cost driver—when gas prices are low, production costs are low and thus CO_2 emissions will increase. This particular fertilizer plant will overhaul its production equipment in 2016, likely resulting in a temporary stoppage of CO_2 supply, and subsequently the CO_2 supply is expected to be permanently reduced. In this case, we know that CO_2 supply will decrease over time, and thus net storage will decrease over time. For projects depending on carbon credits or tax offsets to facilitate storage, the possibility of such interruptions in CO_2 supply may be an unacceptable risk. A variable CO_2 supply directly impacts the cost of a project. Specifically, pipelines and compressors are typically sized for a specific operation and sizing for variable supply may be less efficient, less reliable, and much more costly.



Map depicting the location and pipelines for the two anthropogenic CO_2 sources used during the EOR monitoring effort at the Farnsworth site. Note the rough equidistance of both sources to the EOR site.

Topography: FWU (SWP Development Phase)

CASE STUDY 2.2 — **SWP**

SOUTHWEST REGIONAL PARTNERSHIP ON CARBON SEQUESTRATION (SWP)

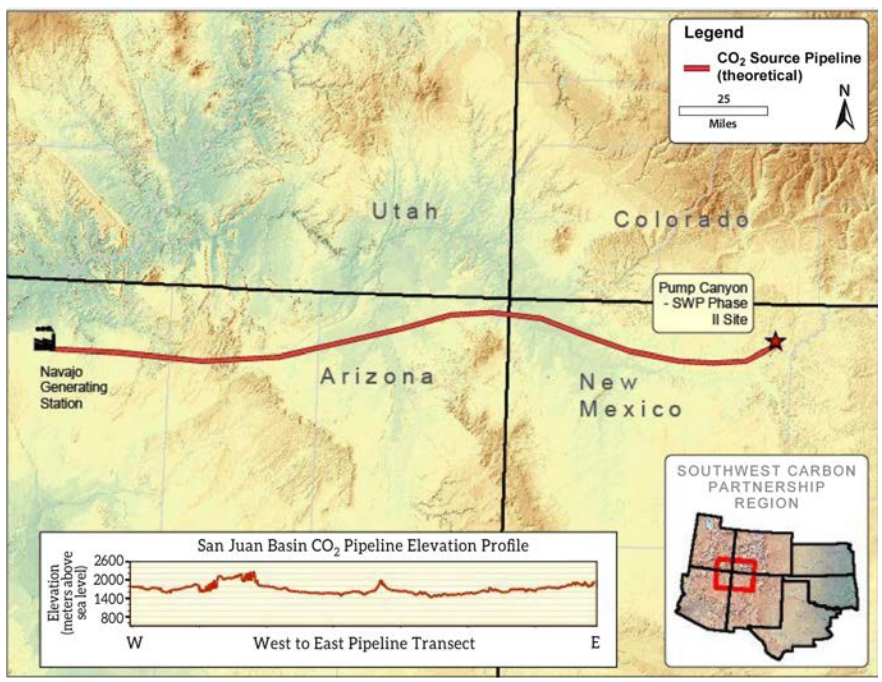
Project Site must be Economically Viable with Respect to Cost of CO_2 Transportation

The cost of CO_2 transportation should be a consideration in the choice of a CCS site. For example, when electric power companies choose a plant location, the decision is in part based on the distance to the fuel source as compared to the amount/distance of transmission lines required. If CCS were included as part of a plant design, then pipeline cost from the source (power plant) to the sink (storage site) would also need to be factored into the decision.

SWP's Farnsworth Unit (FWU) project is located about equidistant from two different anthropogenic CO_2 sources. Several other CCS/EOR opportunities lie within 20 miles of FWU. Thus, the cost of CO_2 supply pipelines could be partially offset by opportunities to exploit multiple injection locations and the ability to switch easily between CO_2 sources if supply and demand dictate changes. Terrain and land use significantly impact CO_2 transport costs. A comparison of terrain and elevation profiles for SWP's Validation Phase project at Pump Canyon, NM, and Farnsworth Unit, TX demonstrates that use of anthropogenic CO_2 (potentially sourced from a generating station in AZ) at the NM site would have been more difficult and expensive. Although the distances are roughly the same, a project at Pump Canyon would contend with more rugged topography, as well as a variety of sensitive areas such as archeological sites and critical wildlife habitat. The table below, published online by Kinder Morgan, summarizes pipeline costs and illustrates that costs for pipelines to FWU was likely almost half the cost for a Pump Canyon project. For economic viability, CCS at Pump Canyon would require closer supply of CO_2 or have some other highly favorable reason for the location.

Kinder-Morgan Pipeline Cost Metrics

Terrain	Capital Cost ($/inch-Diameter/ mile)
Flat, Dry	$50,000
Mountainous	$85,000
Marsh, Wetland	$100,000
River	$300,000
High Population	$100,000
Offshore 150'-200' depth)	$700,000



Map depicting theoretical pipeline from a potential anthropogenic CO_2 source to the SWP Pump Canyon Validation Phase filed project site. The cross-section shows the significant elevation changes of the pipeline. This contributes to increase transportation costs for the project.

3.0 SITE SCREENING

The purpose of Site Screening is to evaluate regions (called Potential Sub-Regions) within a much larger area of interest, such as the entire sedimentary basin. The Site Screening evaluation will identify those Potential Sub-Regions with the highest potential for storage and help eliminate from consideration those that are less preferable. Each Potential Sub-Region is evaluated to determine if there are smaller, separate areas (called Selected Areas) within it that are suitable for more detailed characterization. The end result of the evaluation of all the Potential Sub-Regions is a list of Selected Areas, which are then ranked based on criteria established during Project Definition. The highest-ranking Selected Areas advance to Site Selection for more detailed characterization.

The Site Screening stage is focused on the evaluation of datasets that represent sub-regional and basin-scale geologic characteristics. This stage uses existing data and resources. To keep costs to a minimum when evaluating numerous large sub-regions of a basin, developers should rely on readily accessible data from reliable sources, including state geological surveys, groundwater management districts, oil and gas commissions, and state departments of natural resources.

Case Study 3.1, an example from the MRCSP Ohio River Valley, illustrates the benefits of leveraging piggyback wells, combined with existing data from oil and gas exploration activities in the region.

▶ See page 37

Through the activities of the RCSPs and other research projects, the DOE Carbon Storage Program has also developed extensive data specific to the CO_2 storage potential on a regional basis across the United States and portions of Canada. Information resources include a series of National Atlases (NETL, 2016c), Energy Data eXchange™ (EDX) (NETL, 2016d), and many project reports available on the NETL website (NETL, 2016e).

As shown in Table 3.1, the characterization data needed for Site Screening can be categorized into three components: Regional Geological Data, Regional Site Data, and Social Data. The data are used to perform analyses that focus on addressing key elements of the Site Screening process. A data management plan should also be implemented. Guidelines for these analyses and specific data requirements are summarized in Table 3.1 and discussed further in the sub-sections that follow.

Case Study 3.2, from the BSCSP, illustrates key considerations that should inform a comprehensive data management plan for a given site.

▶ See page 38

Table 3.1. Guidelines for Site Screening.

REGIONAL GEOLOGICAL DATA	Subsurface Data Analysis	Storage Formations	Identify potential storage formations using sub-regional or basin-scale geological and geophysical data. Candidate formations should have geologic characteristics—including porosity, permeability, thickness, salinity, and pore pressure—that make them suitable for storage.
		Adequate Depth	For Potential Sub-Regions, assess minimum depth of injection for achieving adequate protection of USDWs, and evaluate depths at which injected CO_2 will be in a supercritical state for improved storage efficiency.
		Confining Zone	Identify confining zones in Potential Sub-Regions that will be effective for limiting vertical flow of injected CO_2 out of the storage formation.
		Prospective Storage Resources	Candidate storage formations should contain sufficient Prospective Storage Resources beneath a robust confining zone. Prospective Storage Resources for Potential Sub-Regions should be estimated utilizing existing data, including NATCARB and state geological survey data.
REGIONAL SITE DATA	Regional Proximity Analysis	Protected and Sensitive Areas	Identify environmentally sensitive areas in Potential Sub-Regions, and assess potential conflicts with siting of pipeline routes, field compressors, and injection wells. Evaluate potential for surface sensitivities related to wetlands, source water protection, biological diversity, cultural sites.
		Population Centers	Identify population centers using Federal and state census data. Assess the potential for issues with siting carbon storage projects.
		Existing Resource Development	Identify existing resource development in Potential Sub-Regions, and assess potential for conflicts with carbon storage project development. Consider existing or prospective mineral leases, as well the availability of complementary or competing infrastructure.
		Pipeline ROWs	Identify existing pipelines and gathering lines/systems in Potential Sub-Regions. Assess potential for conflicts in routing of pipelines to carbon storage projects, as well as the potential for use or access to existing pipeline ROWs.
SOCIAL DATA	Social Context Analysis	Demographic Trends	Describe communities in and adjacent to Potential Sub-Regions, by examining demographic trends and the social context that may influence public perceptions of a future storage project.
		Land Use	Evaluate trends in land use, industrial development, and environmental impacts in Potential Sub-Regions. Begin to assess community sensitivities to land use and the environment.
	Complete Site Screening	Selected Areas	Review all Potential Sub-Regions, and create a list of Selected Areas based on geologic suitability, regional site suitability, and social context criteria.

Figure 3.1 is a process/information flow chart for the analyses needed for Site Screening. It shows that for each Potential Sub-Region, analysis of the various data components proceeds in parallel and answers questions posed at the decision gates. “No” responses move the analysis to a new Potential Sub-Region, and “yes” responses lead to inclusion on the list of Selected Areas to be ranked and further evaluated during Site Selection.

Prior to initiating each component analysis, a multi-disciplinary team should be assembled to define analyses required to address each of the elements. Similarly to the Project Analysis described in Chapter 2, the team should consider scope, evaluation criteria, resources, and schedule. This process should be conducted to ensure that project needs are met and adequate resources are available to complete all the analyses.

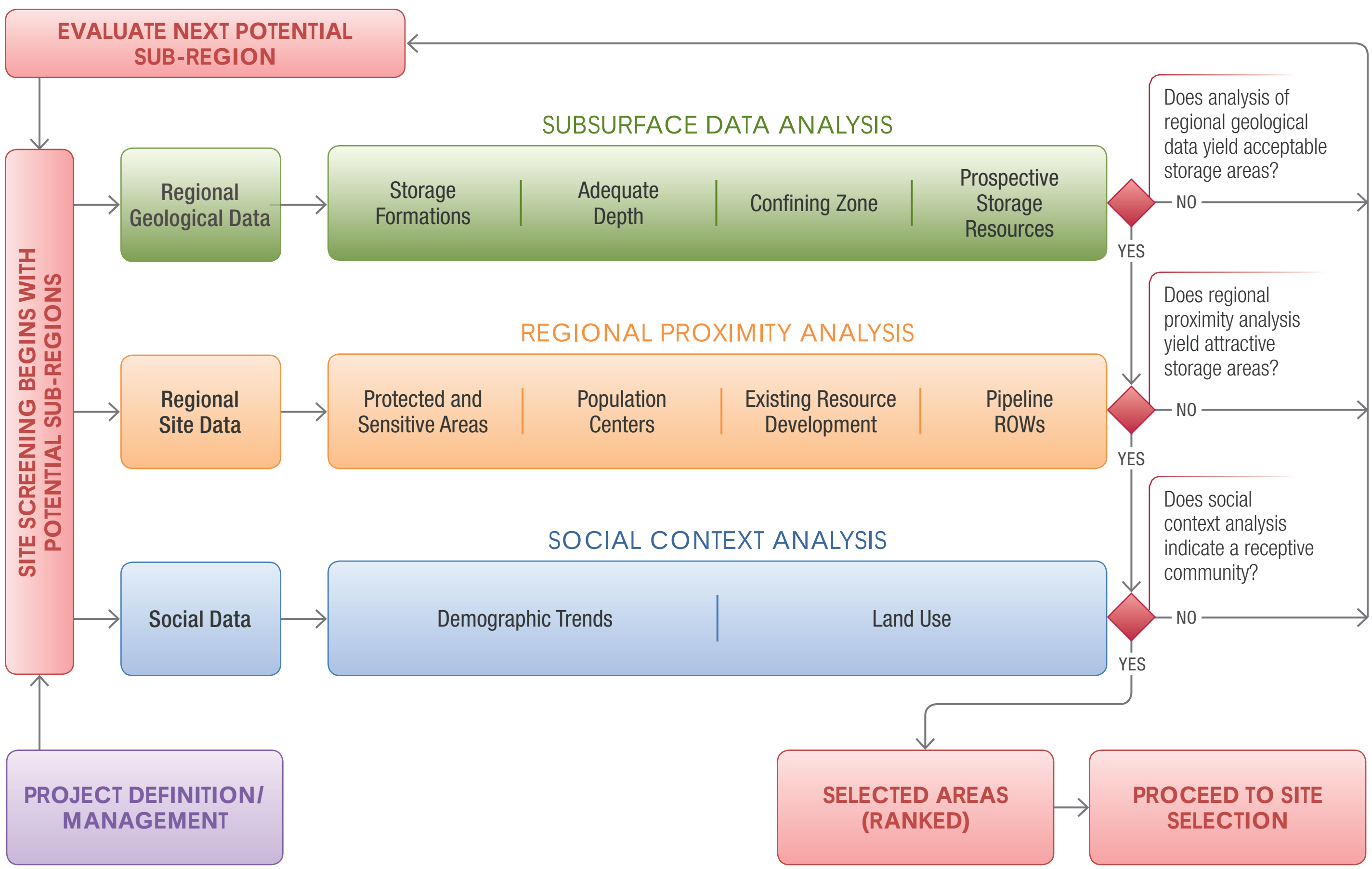


Figure 3.1: Process Flowchart for Site Screening

3.1 SUBSURFACE DATA ANALYSIS

The main objective of subsurface data analyses for purposes of Site Screening is to evaluate geologic data in Potential Sub-Regions, focusing on at least four elements:

i. Storage Formation: Identify regional and sub-regional formations that have geologic characteristics (including porosity, permeability, salinity, in-situ stress/formation fluid pressure [pore pressure]) that are suitable for storage.

ii. Adequate Depth: Ensure that formations have regional extent with sufficient pressure at depth to maintain injected CO_2 in the supercritical state.

iii. Confining Zone: Ensure that an adequate confining zone is present and has sufficient lateral extent to contain injected CO_2 and avoid vertical migration of brine into an underground source of drinking water (USDW).

iv. Prospective Storage Resources: Calculate the prospective storage resource to ensure that formations have sufficient pore volumes and can accept the change in pressure to accommodate planned injection volumes. Calculation of the prospective storage resource follows from, and is informed by the results of analyses in the first three elements.

A brief description of each of these elements is provided below (the reader should also refer back to Figure 3.1 and Table 3.1 to chart the process flow and find the suggested guidelines for assessing these elements). The guidelines should be considered the minimum for data collection and analyses completed through the Site Screening evaluation.

3.1.1 STORAGE FORMATION

DOE is investigating five types of underground reservoirs for geologic CO_2 storage: saline formations, oil and natural gas reservoirs, unmineable coal, organic-rich shale, and basalt formations. The RCSP Initiative has mapped and compiled storage resource data for saline formations, oil and natural gas reservoirs, and unmineable coal within their regions. Organic-rich shale and volcanic and mafic rocks, principally basalt, are being studied further. While most CO_2 storage resources across the United States are present in major onshore sedimentary basins (Figure 3.2), studies are currently underway to identify and map potential offshore sub-seabed reservoirs.

Each reservoir type has its own opportunities and challenges. The five reservoir types currently being studied by DOE for CO_2 storage are described below.

OIL AND NATURAL GAS RESERVOIRS

Oil and natural gas fields, both active and inactive, exhibit geologic characteristics that make them excellent targets for CO_2 storage. An oil or gas “field” is an area consisting of a single reservoir or multiple reservoirs all grouped on, or related to, the same individual geological structural feature and/or stratigraphy. An oil or gas “reservoir” is a porous and permeable underground formation that is confined by impermeable rock and characterized by a single natural pressure system. The overlying confining rocks of oil and natural gas reservoirs have prevented upward migration of hydrocarbons for millions of years. The geologic conditions that trap oil and gas in these reservoirs are also conducive to trapping CO_2. Because these fields have been extensively studied, a large amount of production history, well log, and other data are available. Typically, there is also significant infrastructure already in place that, in some cases, could be utilized for CO_2 storage. As an added benefit, when CO_2 is injected into a mature oil field, it may produce additional oil through a process known as CO_2 enhanced oil recovery (EOR).

DEEP SALINE FORMATIONS

Deep saline formations suitable for CO_2 storage are layers of porous rock that contain formation waters with salinity greater than 10,000 mg/L total dissolved solids (TDS). This water is generally unsuitable for drinking or agriculture.[1] Saline formations are very promising as potential CO_2 storage sites because they are often thicker and more areally extensive than oil and natural gas reservoirs or coal seams. In fact, oil and natural gas reservoirs are located within deep saline formations. Therefore, suitable saline formation CO_2 storage sites may be in close proximity to CO_2 sources, minimizing pipeline transport distance.

Potential storage reservoirs in deep saline formations are characterized by one or more layers of sedimentary rock, such as sandstone, limestone, and dolomite, in one or more layers that have sufficient porosity and permeability for adequate storage and injectivity. To be suitable for storage, these potential reservoirs need to be overlain by a confining

[1] Average seawater is 33,000 mg/L TDS: http://www.ruf.rice.edu/~cbensa /Salinity/index.html.

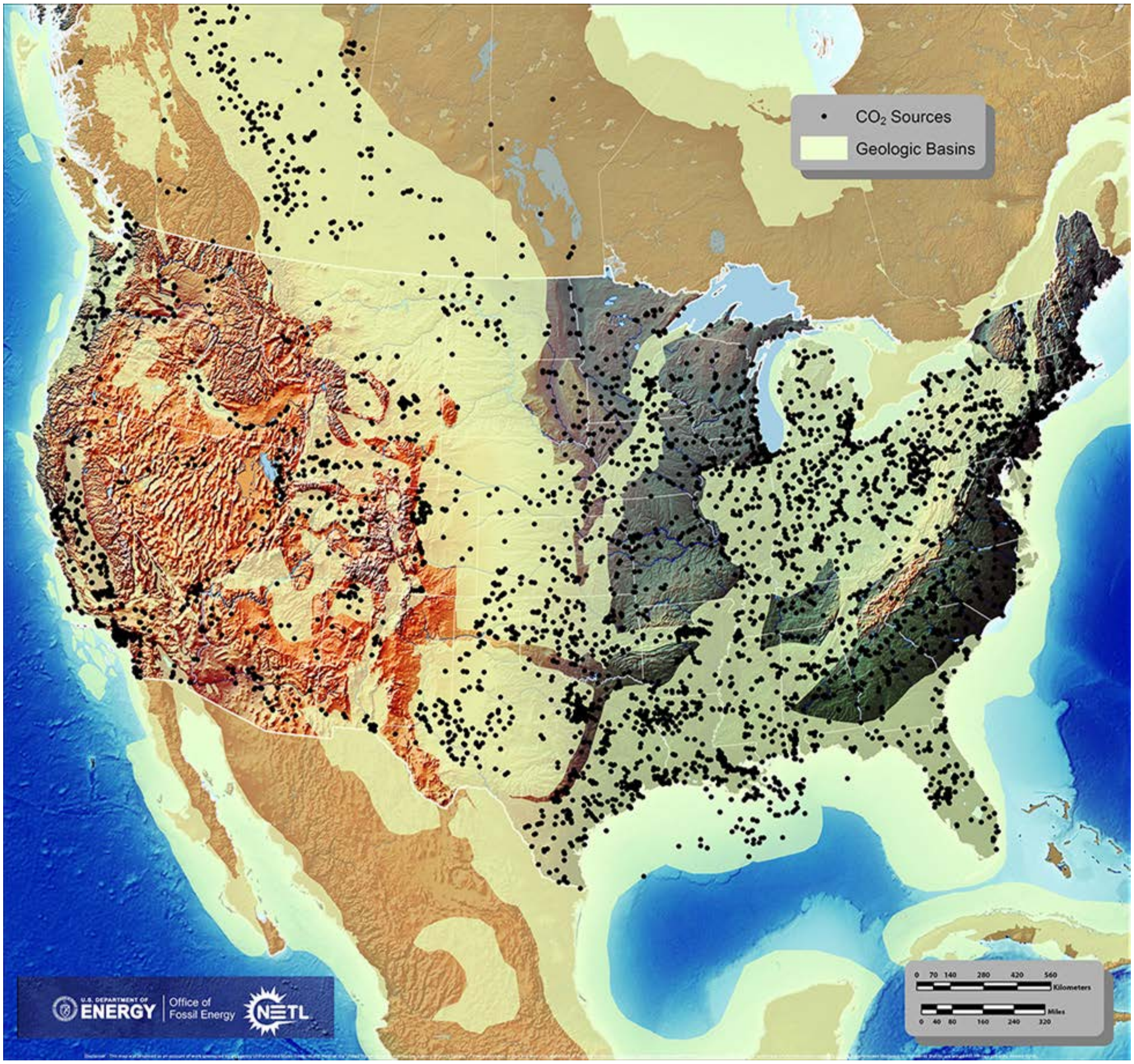


Figure 3.2: Overlay of CO_2 Source Locations and Major Sedimentary Basins in United States and Portions of Canada (NATCARB, 2016)

(Shown are sources emitting more than 10,000 metric tons per year, including agricultural processing plants, cement plants, electric power plants, ethanol plants, fertilizer plants, industrial facilities, petroleum/natural gas facilities, refineries, chemical plants, and unclassified facilities.)

zone that contains one or more layers of low-permeability rock, such as shale or evaporate, and forms a physical barrier that prevents upward migration of the CO_2. Deep saline formations must be shown to effectively trap CO_2, as well as any pressurized brine, to prevent fluids from leaking into a USDW or to the surface and atmosphere. Trapping can be in a structural or stratigraphic closure analogous to those that trap hydrocarbons. Alternatively, effective trapping by a combination of capillary processes and dissolution over a long flow path can be considered.

Finally, the fluid pressure regime (e.g., over-pressure, under-pressure, regional drive[s]) in Potential Sub-Regions needs to be assessed to determine if the reservoir can accept the change in pressure needed to accommodate planned injection volumes. Initial evaluations should be made to determine the area and magnitude of pressure increase due to the injection. Additionally, an evaluation of existing faults that might put constraints on the anticipated amount of pressure buildup should be made. Available regional data on natural seismicity need to be collected and assessed. This includes information on fault locations and tectonic stress state, as well as magnitudes, locations, and recurrence intervals of historical and pre-historical events. This information provides the basis for initial assessment of risk of induced seismicity in Potential Sub-Regions.

Despite the large potential for storage capacity, it is important to note that deep saline formations are less extensively characterized than oil and gas fields and many coal seams. Therefore, more effort is required to complete the Exploration Phase evaluations.

UNMINEABLE COAL SEAMS

Unmineable coal seams are too deep or too thin to be economically mined and thus provide a storage source of adsorbed CO_2. Injected as a gas, CO_2 will adsorb and be stored onto the coal surface. Additionally, all coal seams have varying amounts of methane, referred to as coalbed methane (CBM), adsorbed onto pore surfaces. The concept of enhanced coalbed methane (ECBM) recovery is based upon the fact that coal has a greater affinity for CO_2 than methane. Thus, when CO_2 is injected into the coal seam, methane is liberated and produced, depending on the hydrostatic pressure, while the CO_2 is retained. It is important to note that coal permeability decreases with depth, such that injection is not possible below approximately 900 meters (3,000 feet) without fracturing. Also, coal may "swell" in the presence of CO_2, which reduces the permeability and injectivity. NETL-funded research in this area is focused on increasing the amount of CO_2 that remains on the coal, while minimizing the negative effects of CO_2 on the coal seam's properties (e.g., Reeves, 2001; Koperna, 2009).

ORGANIC SHALE

Shale is characterized by layers of typically clay-rich rock with low permeability, especially in the direction perpendicular to the layering. For this reason, shale functions as an effective confining zone for many reservoirs. Many shale units contain more than one percent organic material, which provides an adsorption substrate for CO_2 similar to that of coal. Organic shale has recently emerged as a source of natural gas in the United States. With prospects of producing shale gas, the issue of CO_2 storage in shale becomes much more complex and needs further examination. To date, little research has been done on achieving economically viable CO_2 injection rates or enhanced gas recovery (EGR) in organic shale, given its extremely low permeability. The technical and commercial feasibility is unknown, but if it proves feasible, organic shale may represent a CO_2 storage resource.

BASALT AND OTHER VOLCANIC AND MAFIC ROCKS

The chemical composition of a number of volcanic and associated rock types (mafic rocks, such as basalt, are rich in magnesium and iron) makes them highly reactive with CO_2, potentially converting the injected CO_2 to a solid mineral form and permanently isolating it from the atmosphere. Basalt research is focused on enhancing the mineralization reactions and increasing CO_2 flow within a basalt formation. Basalt flows, such as those of the Columbia River Basalts in the Pacific Northwest, are believed to have a large potential for permanent CO_2 storage. These flow intervals have generally high permeability and porosity, but their confinement ability has yet to be demonstrated. Although research is being carried out on CO_2 storage in basalt, further validation and development injection tests are anticipated before this rock type is used for commercial injection.

3.1.2 ADEQUATE DEPTH

Compliance with the Safe Drinking Water Act (SDWA) requires that injection occur below USDWs, although the EPA may grant exemptions in some cases of deep fresh water.

In addition, to increase storage security and confidence and to maximize storage potential, injection at depths where CO_2 will be supercritical are favored. Carbon dioxide becomes supercritical at a temperature of 31.3°C (88.3°F) and a pressure of 7.4 MPa (1,071 pounds per square inch

[psi]). Temperatures and fluid pressures (pore pressures) in excess of these values are commonly found onshore at depths greater than 800 meters (2,600 feet), but need to be assessed for each Sub-Region. Under supercritical conditions, CO_2 has a liquid-like density of approximately 500 to 800 kg per cubic meter (31 to 50 pounds per cubic foot), so that the volume of the CO_2 is significantly reduced compared to the gas phase at shallower depths.

Some viable storage opportunities, such as depressurized gas reservoirs, may be available at shallower depths that are not favorable to supercritical conditions. The low pressure of a depressurized gas reservoir provides a lot of storage under conditions of high isolation. However, the CO_2 will be in a gaseous state when it first enters the reservoir.

3.1.3 CONFINING ZONE

At supercritical conditions, CO_2 is less dense than saline water and oil. Its buoyancy provides a driving force for upward movement, potentially out of the reservoir. In addition, unless a reservoir is strongly depressurized, CO_2 will be injected at pressures exceeding the hydrostatic pressure in the reservoir, giving CO_2, associated saline water, and other fluids energy to move outward from the injection point.

It is essential that injection occurs beneath a confining zone that limits the vertical flow of CO_2 into other formations, USDWs, and the atmosphere. A confining zone is made up of one or more geologic barriers, typically low-permeability rock units, which overlie or enclose a storage reservoir. Generally, the low-permeability rock units are composed of fine-grained rocks, such as shales and mudstones, or rocks in which the crystals are closely intergrown, such as well-cemented carbonate, bedded salt, or anhydrite rocks. The small pore throats of these rocks provide a capillary barrier, which does not allow entry of the CO_2 into the pore system. Flow through such rocks is limited to diffusion.

In the Site Screening stage, existing regional geologic data are analyzed to determine the presence of a suitable confining zone in Potential Sub-Regions. This analysis includes determination of formation type, depth, thickness, and lateral extent. Suitable confining zones are laterally extensive, stretching beyond the region where CO_2 injection causes elevated pressures sufficient to lift the contaminated water to a USDW. Significantly more detailed analysis of the confining zone(s) will be necessary in subsequent Site Selection and Initial Characterization stages.

3.1.4 PROSPECTIVE STORAGE RESOURCES

In the Site Screening stage, Prospective Storage Resource estimates are made for the Potential Sub-Regions using regional data on the geologic characteristics of the target injection formation. Key factors influencing calculations include the areal extent, thickness, average porosity, and density of the CO_2 at reservoir conditions. These initial estimates of the Prospective Storage Resources will be further refined during Site Selection and characterization of storage sites.

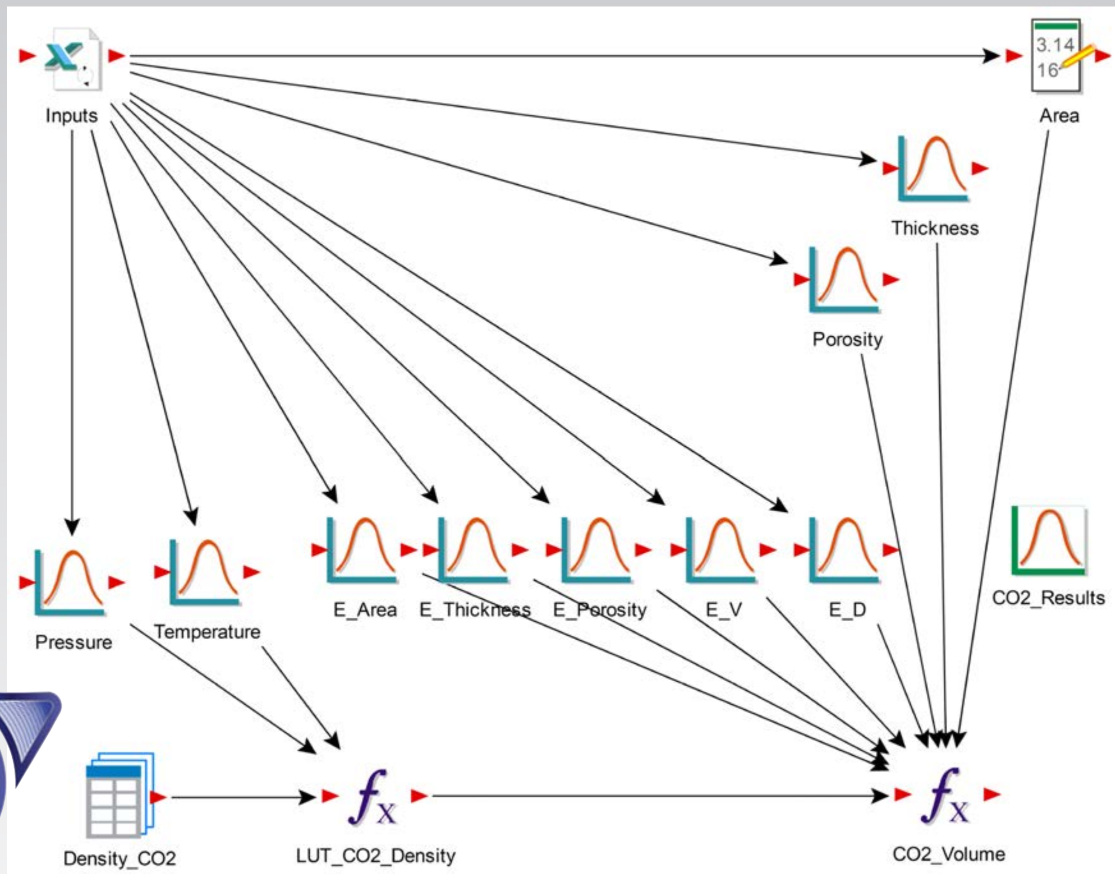
Case Study 3.3, from the PCOR Partnership, provides useful guidelines for calculating the effective CO_2 storage resource in deep saline formations.

▶ See page 39

A detailed description of the DOE methodology for estimating Prospective Storage Resources for oil and natural gas reservoirs, saline formations, unmineable coals seams, and shale is available in NETL, 2015; Goodman et al., 2011; Goodman et al., 2013; Goodman et al., 2014; and Levine et al., 2016. A summary of the DOE/FE/NETL CO_2-SCREEN tool is provided on page 32.

The CO_2 Storage prospeCtive Resource Estimation Excel aNalysis (CO_2-SCREEN) is a tool developed by DOE/FE/NETL to calculate the prospective CO_2 storage resource for saline formations. Prospective CO_2 storage resource is an estimate of the mass of CO_2 that can be stored in a geologic formation. The ability to accurately predict the CO_2 storage resource is required to make high-level, energy-related government policy and business decisions. CO_2-SCREEN consists of an Excel spreadsheet containing geologic inputs and outputs, linked to a GoldSim Player model that calculates prospective CO_2 storage resources via Monte Carlo simulation.

The CO_2-SCREEN tool is available to the public and resides in a private EDX Collaborative Workspace for BETA testing.



The GoldSim Player submodel structure of CO_2-SCREEN. This submodel is composed of an Excel input function, data distributions for the input parameters, a lookup table (LUT) to calculate CO_2 density, embedded equations to calculate prospective CO_2 storage resource, and generated results that are relayed to the main model to be exported to the corresponding Excel file.

Figure 3.3: CO_2 Storage prospeCtive Resource Estimation Excel aNalysis (CO_2-SCREEN).
Developed by DOE/FE/NETL.

Table 3.2 shows estimates, compiled by the National Carbon Sequestration Database and Geographic Information System (NATCARB) and collected by the RCSPs, of Prospective Storage Resources in oil reservoirs, natural gas reservoirs, unmineable coal, and saline formations in the United States and parts of Canada (NETL, 2016c). See Figure 1.3 for geographic extent of each RCSP.

Table 3.2: Atlas V Estimates of CO_2 Stationary Source Emissions and Estimates of CO_2 Storage Resources for Geologic Storage Sites (NETL, 2016c)

CO_2 Stationary Sources

Saline Formations

Estimates of CO_2 Stationary Source Emissions and Estimates of CO_2 Storage Resources for Geologic Storage Sites

RCSP or Geographic Region	CO_2 Stationary Sources		CO_2 Storage Resource Estimates (billion metric tons of CO_2)								
	CO_2 Emissions (million metric tons per year)	Number of Sources	Saline Formations			Oil and Gas Reservoirs			Unmineable Coal Areas		
			Low	Med***	High	Low	Med***	High	Low	Med***	High
BSCSP	115	301	211	805	2,152	<1	<1	1	<1	<1	<1
MGSC	267	380	41	163	421	<1	<1	<1	2	3	3
MRCSP	604	1,308	108	122	143	9	14	26	<1	<1	<1
PCOR*	522	946	305	583	1,012	2	4	9	7	7	7
SECARB	1,022	1,857	1,376	5,257	14,089	27	34	41	33	51	75
SWP	326	779	256	1,000	2,693	144	147	148	<1	1	2
WESTCARB*	162	555	82	398	1,124	4	5	7	11	17	25
Non-RCSP**	53	232	--	--	--	--	--	--	--	--	--
Total	3,071	6,358	2,379	8,328	21,633	186	205	232	54	80	113

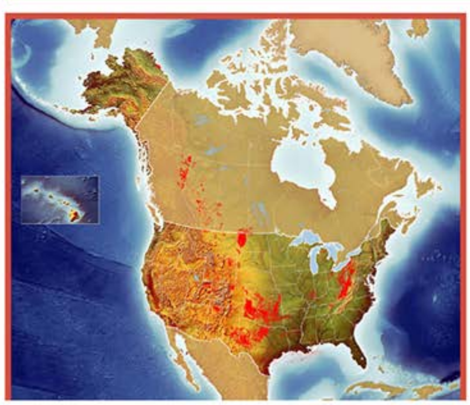
Source: U.S. Carbon Storage Atlas – Fifth Edition (Atlas V); data current as of November 2014

* Totals include Canadian sources identified by the RCSP

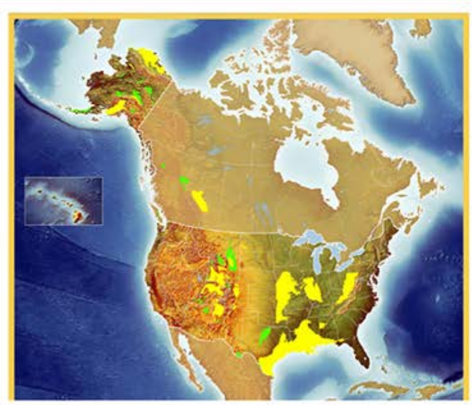
** As of November 2014, "U.S. Non-RCSP" includes Connecticut, Delaware, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, and Puerto Rico

*** Medium = p50

Oil Reservoirs



Natural Gas Reservoirs



Unmineable Coal Areas

3.2 REGIONAL PROXIMITY ANALYSIS

The second component of the Site Screening stage includes an analysis of Regional Site Data to determine potential regional or sub-regional proximity issues. At a minimum, four site-specific features could have an impact on the attractiveness of a sub-region: (i) Protected and Sensitive Areas, (ii) Population Centers, (iii) Existing Resource Development, and (iv) Pipeline Right-of-Ways (ROWs). While the presence of any of these features does not constitute a technical reason to eliminate a site, their presence could require additional analyses, contingencies, project delays, and increased project costs. Careful evaluation of potential issues concerning land access and use should also be carefully evaluated during this process.

3.2.1 PROTECTED AND SENSITIVE AREAS

Actions must be taken to protect the land, air, and water in the vicinity of a storage project during characterization, development, operation, and closure. During the Site Screening evaluation, consideration should be given to environmentally sensitive features in Potential Sub-Regions. Protected and sensitive areas such as wetlands, national or state parks, protected or historical areas, Native American tribal lands, and species-sensitive areas may require additional measures to protect them. As a result, it may be advisable to exclude them during Site Screening or to consult the corresponding regulatory authorities about additional requirements. This is especially important if Federal funds will be used, as this triggers NEPA requirements, which specifically consider these factors.

WETLANDS

Any modifications to wetlands in the United States will likely be regulated, in some capacity, by Federal, state, and/or local governing authorities. Section 404 of the Clean Water Act (CWA) (EPA, 2016b) provides the regulatory framework for the Federal government's role in regulating activities that impact wetlands. The Federal program is administered by the U.S. Army Corps of Engineers (Corps) with oversight by EPA. Section 404 of the CWA regulates the discharge of dredged and fill material into U.S. waters, including wetlands. The regulations under Section 404 of the CWA may be applicable if a project requires disposal of fill material into waterways. Wetland replacement regulations, similar to "mitigation banking," are commonly active on the state level with the goal of replacing any lost wetland acreage with constructed wetlands. Site development in or near wetlands (including possible transportation through a wetland) that impacts wetland integrity may require that alternative wetlands be set aside to replace the impacted acreage. In Pennsylvania, for example, the Department of Environmental Protection governs wetland replacement regulations and requires the replacement of lost wetland acreage with constructed wetlands, with a ratio currently of 1:1 with a permit and 2:1 without a permit. EPA guidance on wetlands is available at EPA, 2016c.

SOURCE WATER PROTECTION AREAS[2]

Source water is water from streams, rivers, lakes, or underground aquifers, typically untreated, that is used to provide public drinking water and wells for private consumption. Although this water usually requires treatment before being consumed, these waters are protected to the extent possible from contamination. The SDWA requires that the states develop EPA-approved programs to carry out assessments of all source waters in the state. The source water assessment is a study that defines the land area contributing water to each public water system, identifies the major potential sources of contamination that could affect the drinking water supply, and then determines how susceptible the public water supply is to this potential contamination. There may be Federal or local requirements relating to activities that take place nearby, or that have the potential to impact these waters. Notably, sole source aquifers might trigger additional project reviews as part of the permitting process.

PROTECTED AREAS

A protected area is defined as an area of land and/or sea where protection and maintenance of biological diversity, natural resources, and cultural effects are required through legal or other means. Examples of protected areas include national or state parks, national monuments, or areas with important historical or cultural significance. In the United States, protected areas are managed by an assortment of different Federal, state, local, and tribal authorities.

[2] This section draws extensively on information provided by U.S. EPA's Source Water Protection Program website: http://cfpub.epa.gov/safewater/sourcewater/sourcewater.cfm?action = Basic&view=general.

SPECIES PROTECTION

In the United States, CO_2 storage projects cannot pose a threat to the well-being of protected wildlife, flora, or fauna in the region or the habitat in which they live. In the oil industry, there are a number of methods for successfully developing oil and natural gas infrastructure in such areas, but these operations are carefully planned and in some cases incur additional project time and costs. During Site Screening, project developers should identify and assess the impact on schedule and costs of any protected species or wildlife migration patterns in Potential Sub-Regions.

3.2.2 POPULATION CENTERS

To obtain permits, a CO_2 storage project must be able to demonstrate that injected CO_2 will remain contained in the subsurface. The fact that there are a number of analogous injection practices, such as natural gas storage, located in densely populated areas suggests that the presence of a population center near a candidate site is not a reason, per se, to reject that site. However, a number of issues must be carefully examined when considering a site in a densely populated area. These include the challenges associated with acquiring permission for Site Characterization activities, rights to pore space, and access to ROWs and possible high land values. These concerns could lead to project delays and increased costs in the future. Therefore, a project developer may prefer sites that are not near population centers. During Site Screening, project developers should identify population centers and assess the potential overlap of densely populated areas and candidate Selected Areas in Potential Sub-Regions.

3.2.3 EXISTING RESOURCE DEVELOPMENT

Locating a CO_2 storage project near existing hydrocarbon resource developments can lead to benefits and concerns. Existing upstream oil and natural gas developments, for example, may provide valuable information about the potential storage reservoir with minimal investment. However, every deep well through the candidate injection zone is a breach of the natural confining zone. The cement and casing integrity of those wells needs to be understood, if the site is later qualified for injection and storage. Production wells generally do not have cement between the production zone and the surface casing; this may cause wells to provide unacceptable pathways from the one zone to another above the reservoir. For this reason, careful analysis should be made of all existing infrastructure (subsurface and surface, industrial, and non-industrial) to determine the extent to which their presence might impact proposed injection and storage operations as potential leakage pathways.

Furthermore, as the petroleum industry evolves, new technologies are enabling resources that were once considered technically infeasible for becoming economic sources of hydrocarbons (e.g., producing shale reservoirs). In some instances, a shale formation that was being considered a confining zone for geologic storage may also be considered an economic reservoir for the petroleum industry. Regional analysis of the existing and competing resource developments should be considered against the ranking criteria.

3.2.4 PIPELINE RIGHT-OF-WAYS (ROWS)

During Site Screening, proximity to CO_2 pipelines and existing ROWs should be evaluated. The construction of pipelines can be capital intensive. A preliminary screening should evaluate a CO_2 storage project's pipeline needs and the existing CO_2 pipeline network in Potential Sub-Regions. If any exist, it is necessary to rate the size, capacity, and age of the pipelines. If no pipeline infrastructure exists, the developer may prefer a Potential Sub-Region with potential injection formations that are located closer to the CO_2 source.

It may be possible to use existing pipeline ROWs or infrastructure (ie., non-CO_2 pipelines) The existence, condition, and availability of access to existing pipelines in acceptable proximity to the regions of interest should be carefully evaluated. Many existing pipelines are unlikely to be suitable for conversion to supercritical CO_2 service due to pressure limitations and materials used. This data may be available from state public utility regulators or obtained from oil and gas data vendors.

3.3 SOCIAL CONTEXT ANALYSIS

During Site Screening, the objective is to develop a general sense of the communities in the sub-region. This includes consideration of the public outreach implications based on the land ownership patterns, pore-space issues, local and regional governance structures, and the necessary permits and approvals. The project developer should review readily accessible sources of information for (i) Demographic Trends, (ii) Social Context, and (iii) Land Use and Environmental History. These insights can be used to understand how a community may view CO_2 storage, the strategies for appropriate community engagement, and the perceived benefits and risks of the project for the community. This information feeds a preliminary social characterization that will be expanded during the Exploration Phase. Further, it may be useful to review back issues of local and regional newspapers within the sub-region to get a better understanding of community perspectives on energy, climate, the economy, and other related issues.

3.3.1 DEMOGRAPHIC TRENDS

Demographic trends can provide insight to the project developer's understanding of the social context across the region being considered. Demographic data is readily available online at sites such as the U.S. Census database or state economic development websites. In addition, it may be useful to review online academic journals or reports and local media archives to gain additional perspectives in demographic trends. The purpose of this research is to develop a preliminary understanding of the communities in the sub-region where a project might be located and the socio-economic issues they face.

3.3.2 SOCIAL CONTEXT

Building on demographic data, additional research can help round out an understanding of the social context that may influence public perceptions of a potential CO_2 storage project. During the Site Screening stage, research should be limited to readily accessible sources, including review of local websites and local and regional media archives and, interviews with project team members who may have direct experience in the candidate sub-region. This can help answer questions about stakeholder relations between the project sponsor (including any major partners or contractors) and the community; identify general attitudes regarding climate change and energy; and specify general structures of local governments for decision making (both formal and informal decision making).

3.3.3 LAND USE AND ENVIRONMENTAL HISTORY

It is important to assess the land use and environmental history in regions being considered for a CO_2 storage project. This history can provide insight for answering questions such as: Is the land primarily industrial? Are communities used to seeing well-drilling operations, seismic acquisitions, or pipeline construction and use? Is there a strong agricultural presence in the region? Are there environmentally sensitive areas of concern in the region? Is there any history of environmental problems, particularly any associated with an industrial project? Project developers can collect this information by reviewing economic and industrial activity databases, permitting and regulatory databases, and by reviewing the online sources and personnel referenced above. Understanding the land use in a region will aid in assessing the potential perceived risks and benefits from a project.

3.4 DEVELOPING THE LIST OF SELECTED AREAS AND RANKING

Site Screening involves a broad review of suitable Potential Sub-Regions within a basin. The Site Screening process results in identification of Selected Areas that meet geologic screening, proximity, and social context criteria, as well as suitability for injection based on criteria established during Project Definition. The highest-ranked Selected Areas will be evaluated further during Site Selection. Data on all Selected Areas should be kept up-to-date as a contingency in case the highest ranked area should become untenable for development.

3.5 RCSP CASE STUDIES

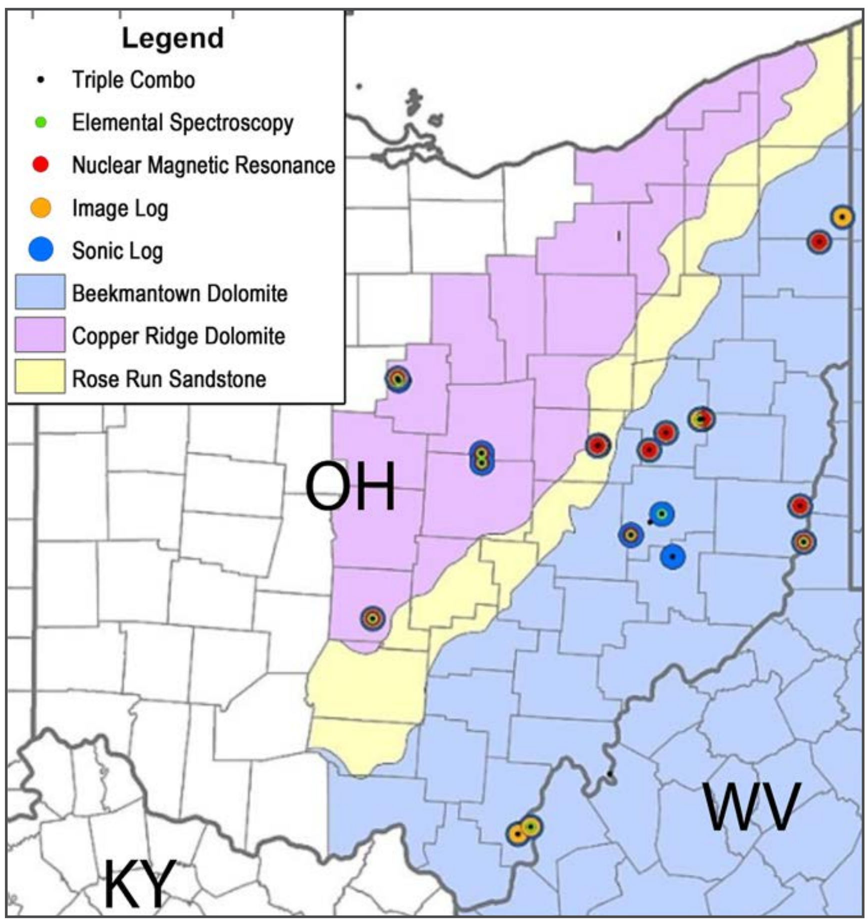
CASE STUDY 3.1 — **MRCSP**

MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

Leverage Piggyback Wells as Opportunities for Advanced Geologic Data Collection

Regional geologic characterization using decades-old publicly available data can be difficult. Drilling new wells for the purposes of site screening and selection is cost-prohibitive over an expansive geographic region with discontinuous geologic formations and attributes. One way of gaining insight into a geographically complex region is by combining all available historical data with data from new wells that have advanced geologic data. This method provides extensive coverage from the existing regional data and high-quality localized data. To expand geologic datasets more cost-effectively, wells being drilled for commercial purposes are selected for "piggyback" opportunities. Advanced datasets are collected during or after drilling, which can include basic and advanced logs, whole core and sidewall cores, and flowmeter and injection testing. The data collected is beneficial both to the well operator (who would not normally collect advanced data) and to the Midwest Regional Carbon Sequestration Partnership (MRCSP) project proponents.

Piggyback locations, combined with a large existing dataset generated by older oil and gas exploration, are helping identify potential storage reservoirs and caprock formations. Well data from Ohio, Michigan, Kentucky, West Virginia, and Pennsylvania are being studied to characterize a complex region along the Ohio River Valley to locate potential storage sites (see figure below). Key steps in the research include: systematic analysis of existing well log and seismic data to identify potential reservoirs and corresponding sealing formations; participation in piggyback wells to cost-effectively gather new data; use of advanced geologic data from new wireline logs and core to correlate new data with historically available data; detailed geologic analysis to assess regional extent; and reservoir modeling to estimate capacity and injectivity. In addition to evaluating formations suitable for receiving and storing injected CO_2, the research also investigates overlying formations that provide barriers to prevent upward migration of CO_2 out of the reservoirs.



A subset of MRCSP piggyback wells in Ohio showing advanced logs collected for each well.

CASE STUDY 3.2 — **BSCSP**

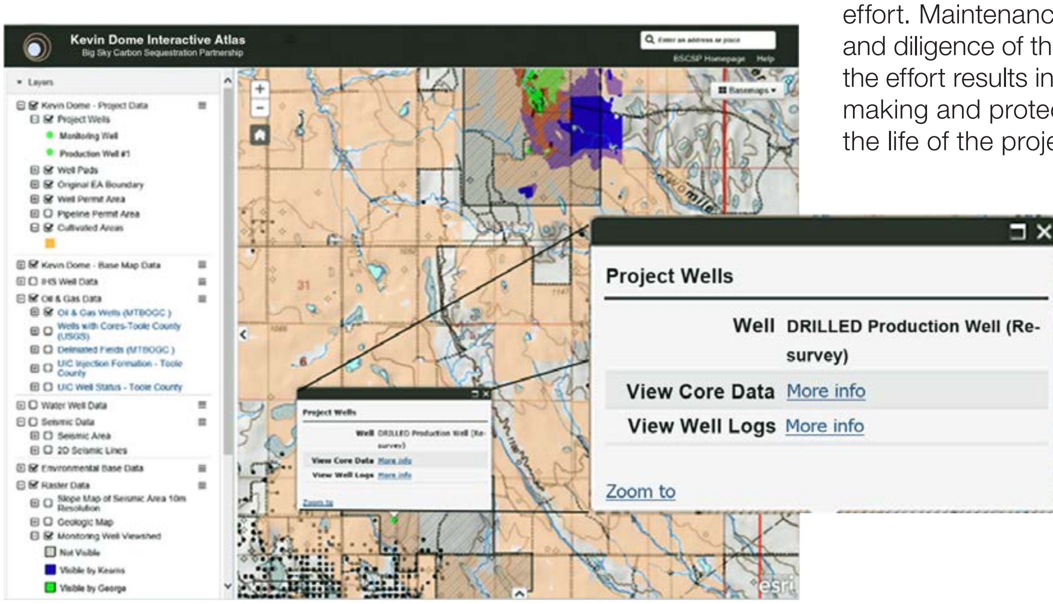
BIG SKY CARBON SEQUESTRATION PARTNERSHIP (BSCSP)

Develop a Data Management Plan

The data required to characterize a site's viability for carbon storage is diverse in topic and format and must be accessible across varying levels of expertise. Data management and quality assurance have impacts on project decision making, financial planning, permitting compliance, stakeholder acceptance, and the ability to achieve project objectives. It is best to begin planning methods for data documentation, communication, sharing, and archival early in the characterization process. A data management plan should be developed and maintained as a working document, modified to meet the changing needs of the project and allowing adoption of new technologies.

Key considerations for a data management plan include: the types and format of information anticipated, quantity of data over the project's lifespan, who will use the data, how it will be used, retention time and archival requirements, use restrictions, and security requirements. In the case of a successful injection project, data management begins during site screening and may continue through the Underground Injection Control (UIC) Class VI Post Injection Site Care period—a duration of more than 50 years. With consideration of this time period, the plan should (1) address how data will be migrated to new formats, (2) set guidelines for metadata and version documentation, (3) establish processes and schedules for backups, and (4) institute organizational data policies and responsibilities.

Implementation of a data management plan begins with cyberinfrastructure development. However, a robust system also relies on user buy-in and responsibility. The Big Sky Carbon Sequestration Partnership's (BSCSP) deployment of simple-to-use tools and clear management strategies has proven vital for data communication, project planning, and fieldwork management. The partnership hosts several secure, redundant, and scalable servers at Montana State University that function as a data repository with backup procedures to archive datasets and prevent data loss. Spatial data is hosted in a geodatabase, which has the benefits of standardized metadata and versioning. One of the most well-received and useful tools has been the development of online mapping applications. BSCSP uses ESRI's ArcGIS API for JavaScript to build interactive maps (see figure below) that are relatively quick to deploy, provide a simple interface for non-GIS users working in remote locations, and are structured for version and quality control, allowing registered users to interact with and edit data in the project's enterprise geodatabase. Planning and development of these resources requires effort. Maintenance relies on the adoption and diligence of the project team. However, the effort results in more informed decision-making and protects data assets through the life of the project.



BSCSP's interactive project Atlas, available to partners through the web browser.

CASE STUDY 3.3 — **PCOR**

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP

Considerations for Proper Estimation of CO_2 Storage Resource in Deep Saline Formations

The evaluation of potential CO_2 storage targets can differ in terms of scope, budget, and available data. However, the basic calculation of the effective CO_2 storage resource of a deep saline formation is a well-defined task (NETL, 2015; Goodman et al., 2011) and can be estimated using a volumetric equation:

$$MCO_2e = A \times h \times \varphi \times \rho CO_2 \times E \text{ [Eq. 1]}$$

Total area (A), gross formation thickness (h), and total porosity (φ) terms account for the total bulk volume of pore space available. The value for CO_2 density (ρ) converts the reservoir volume of CO_2 to mass. The storage efficiency factor (E) represents the fraction of the total pore volume that can be occupied by the injected CO_2.

Although volumetric calculations such as Eq. 1 are straightforward, misapplications of the efficiency factors commonly occur and may ultimately lead to under- or overestimation of the effective storage resource potential of the formation under investigation. A critical component of the CO_2 storage equation is the storage efficiency factor (E), and the choice of which efficiency term to apply is directly related to the amount of information known about the formation's area, thickness, porosity, and pressure boundary conditions.

In an open system, E accounts for the portion of the geologic media that is available for CO_2 storage and the fraction of that pore space where CO_2 can displace the original formation fluids (Equation 2). The fraction of the formation volume that is amenable to CO_2 storage (E_{geol}) is the product of the formation's net-to-total area ($E_{An/At}$), the net-to-gross thickness ($E_{hn/hg}$), and the effective-to-total porosity ($E_{\varphi eff/\varphi tot}$) (Equation 3).

$$E_E = E_{geol} * E_D \text{ [Eq. 2]}$$

$$E_{geol} = E_{An/At} * E_{hn/hg} * E_{\varphi eff/\varphi tot} \text{ [Eq. 3]}$$

The suitable portion of the formation (E_{geol}) is the geographic area where depths exceed 800 meters (assuring high density CO_2) and where the salinity of the formation fluids exceed 10,000 parts per million (ppm). In most site characterization efforts, there is enough existing information to determine the extent of a target formation that meets these criteria (structure maps, well logs, etc.). If this suitable area of formation can be determined, it is unnecessary to determine the total formation extent and, thus, the net-to-total area ratio ($E_{An/At}$) (it effectively becomes one). Simply having an understanding of the area of suitable formation will result in a greater than threefold increase in storage resource value at the P10 confidence level and nearly double the storage resource value at the P90 level (Peck, 2014). If there is an understanding of the net-to-gross thickness of the formation, such as through previous work or well log interpretation, then an even higher value (and confidence) of storage resource can be obtained. This greater confidence leads to better informed decisions regarding the suitability of the candidate site and its potential to meet the CO_2 storage resource needs of a project.

4.0 SITE SELECTION

The purpose of Site Selection is to further evaluate Selected Areas and develop a short list of Potential Sites suitable for Site Characterization. Site Selection utilizes and confirms the existing data and analyses from Site Screening and augments them with additional, proprietary, or other purchased data to evaluate characteristics of the Selected Areas. This stage, analogous to the second project status of an oil exploration program, called a "Lead," includes evaluation of five technical and nontechnical components: Subsurface Geologic Data, Regulatory Requirements, Model Data, Site Data, and Social Data. As in Site Screening, prior to initiating the analyses of the Selected Areas, a multi-discipline team should define the analyses to be conducted for each of the components. The analyses should incorporate, at a minimum, the elements described in Table 4.1, and consider scope, evaluation criteria, resources, and schedule. Guidelines for these analyses and specific data requirements are summarized in Table 4.1 and discussed further in the sub-sections that follow.

Case Study 4.1
(SECARB Anthropogenic Test)
▶ See page 55

and

Case Study 4.2
(BSCSP Kevin Dome Project)
▶ See page 56

provide two real-world examples of how projects make the transition from Site Screening to Site Selection.

Figure 4.1 is a process/information flow chart for the analyses needed for Site Selection. It shows that for each Selected Area, analysis of the various data components proceeds in parallel towards answering the questions posed at the decision gates; "no" responses move the analysis to a new Selected Area, and a "yes" response leads to inclusion on the list of Potential Sites to be ranked and further evaluated during Site Characterization.

Table 4.1: Guidelines for Site Selection

SUBSURFACE GEOLOGICAL DATA	Subsurface Data Analysis	Storage Reservoir	Identify storage reservoirs and injection zones within Selected Areas. Develop stratigraphic and structural framework diagrams that illustrate suitable storage reservoirs and injection zones of interest, using all available well and outcrop data.
		Confining Zone	Analyze confining zones in Selected Areas. Create stratigraphic and structural framework diagrams to illustrate areal extent, thickness, lithology, porosity, permeability, capillary pressure, and structural complexity of suitable confining zones, based on existing data.
		Trapping	Establish baseline geomechanical characteristics of targeted injection and confining zones.
		Mechanism	Evaluate trapping mechanisms for Selected Areas using available well, outcrop, and seismic data.
		Potential	Establish hydrogeological characteristics of injection and confining zones to assure reliable containment of injected CO_2.
		Injectivity	Perform initial estimate of injectivity of candidate injection zones in Selected Areas, using available production history data, hydrologic test data, and analyses of core plugs.
REGULATORY REQUIREMENTS	Regulatory Issue Analysis	Well Classification	Review Federal and state rules for injection wells, specifically UIC Class II and Class VI rules. Consider regulatory requirements for permitting, construction, operation, maintenance, and closure.
		Corrective Action	Review UIC requirements for corrective action for existing wells in Selected Areas, and specifically within the AoR of any planned injection wells.
		Injection Pressure	Review regulatory requirements for establishing the presence and adequacy of injectivity of candidate injection zones, based on existing structural and stratigraphic data.
		Containment Mechanisms	Review regulatory requirements for demonstrating long-term integrity of containment mechanisms; identify potential containment risks and mitigation actions.
		Liability	Review provisions for addressing financial assurance and liability for CO_2 injection and storage in Selected Areas. Incorporate state and Federal requirements into project plan and budget.
MODEL DATA	Model Development	Modeling Parameters	Identify types of models and modeling parameters needed to characterize the storage reservoir, confining zone, and fluid properties for Selected Areas.
		Data Requirements and Cost	Identify data requirements to optimize modeling results; conduct cost vs. benefit analysis to determine value of acquiring new data.
		Boundary Conditions/ Uncertainty	Identify and characterize uncertainties in modeling results; select boundary conditions which minimize uncertainties in modeling results.
		Existing Seismic Data	If available, integrate existing seismic data in development of static and dynamic models for Selected Areas.
SITE DATA	Site Suitability Analysis	Infrastructure	Evaluate infrastructure needs for Selected Areas, including injection and monitoring wells, compression equipment, transportation pipelines, and monitoring equipment.
		AoR Requirements	Estimate AoR, and assess potential surface and pore space ownership issues. Model results should indicate pressure and plume migration impacts on AoR.
		Surface Access	Evaluate potential surface access issues for Selected Areas. Include mitigation plan for potential access and environmental issues.
		Pore Space Ownership	Evaluate pore space ownership rules for Selected Areas, including mineral rights and unitization provisions. Identify pore space owners potentially impacted by plume migration.
SOCIAL DATA	Preliminary Social Characterization	Gather and Assess Social Data	Conduct a more detailed evaluation of social data for communities within Selected Areas. Evaluate perceived concerns and benefits. Conduct interviews with key stakeholders.
	Complete Site Selection	Potential Sites	Frame Site Characterization Plan and Site Development Plan. Complete an economic feasibility analysis for each site. Identify and rank Potential Sites for Site Characterization.

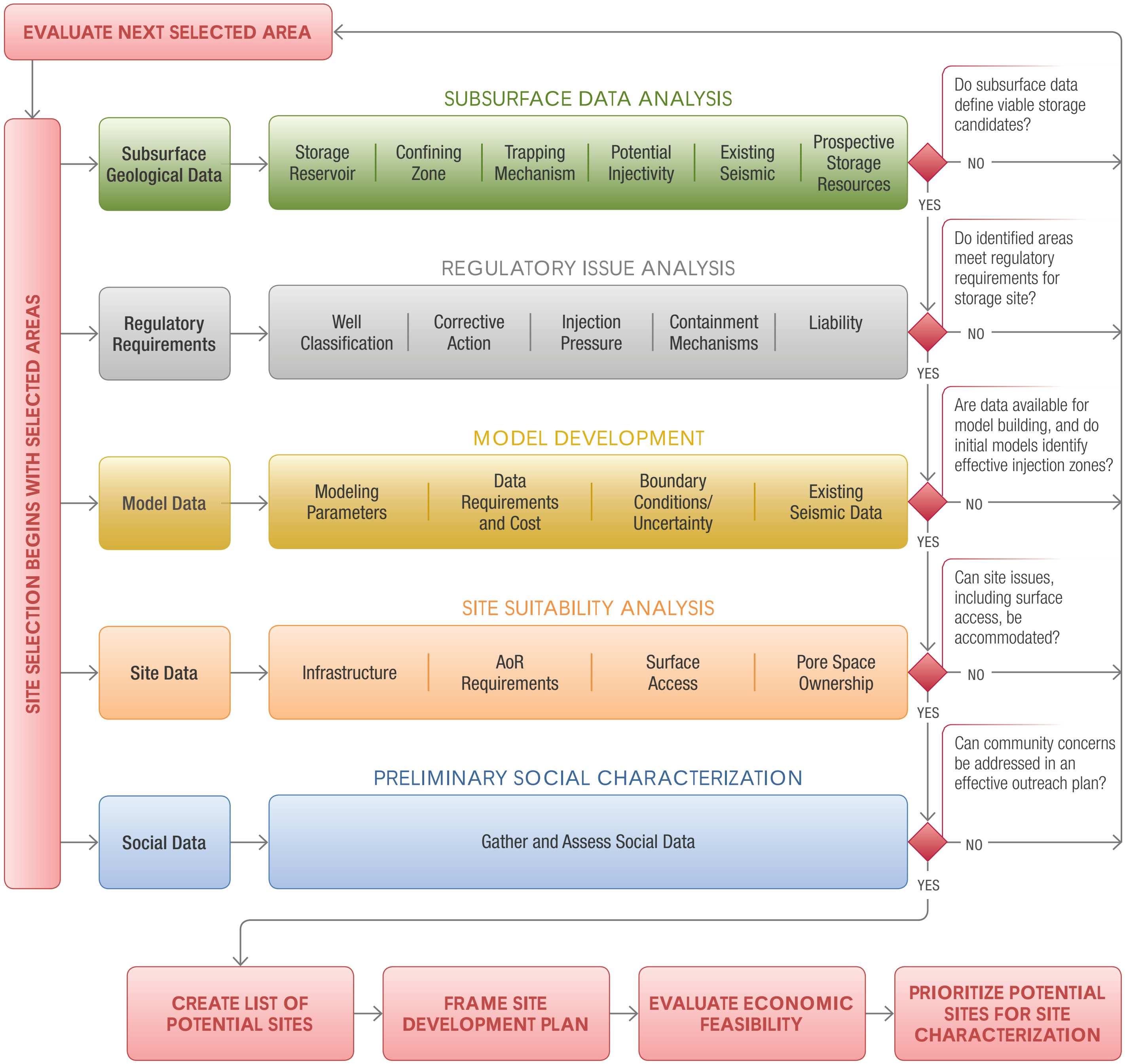


Figure 4.1: Process Flowchart for Site Selection

4.1 SUBSURFACE DATA ANALYSIS

The Site Selection process builds on the geologic evaluation conducted during Site Screening to provide greater detail, improved understanding, and reduced uncertainty in the structure and properties of the subsurface in Selected Areas. For Site Selection, Subsurface Data Analyses carried out in the Subsurface Geologic Evaluation component are focused on six primary elements: (i) Storage Reservoir; (ii) Confining Zone; (iii) Trapping Mechanism; (iv) Potential Injectivity; (v) Existing Seismic; and (vi) Prospective Storage Resources.

4.1.1 STORAGE RESERVOIR

During Site Screening, formations containing reservoirs suitable for storage were identified. In Site Selection, these formations are subjected to more detailed analysis to identify specific storage reservoirs and potential injection zones suitable for CO_2 injection and storage. If a site is chosen for development, actual injection would take place at one or more intervals within an injection zone, but identification of these intervals will not take place until the Site Characterization stage of the project.

To identify suitable storage reservoirs and potential injection zones, the project developer should develop a coarse stratigraphic and structural framework for the Selected Areas. This initial framework correlates available well log data within the Selected Area to map the top and base of storage reservoirs and heterogeneities within them. Outcrops are another potential source of data.

Case Study 4.3, from the PCOR Partnership's Bell Creek Oilfield Project, is an example in which outcrop data supplied valuable details about subsurface reservoir structure and facies heterogeneities.

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The initial stratigraphic framework should highlight significant stratigraphic packages (e.g., sequences, unconformities, flooding surfaces, etc.) and pinch-outs that control the flow system. A framework diagram will also indicate thicknesses and lateral extent of storage reservoirs containing suitable injection zones. The initial structural framework should highlight significant features, such as faults and folds, which may control fluid flow. In some instances, multiple suitable injection zones may occur at different depths and should be mapped and assessed. Reservoir and injection zone thickness maps (isopach maps) can be layered onto the initial framework diagram.

The project developer's level of confidence in the accuracy of the stratigraphic and structural framework will depend on the density of available data within the area. Purchase and analysis of existing seismic data may be considered to augment well log data. This decision should be based upon a cost/benefit analysis.

4.1.2 CONFINING ZONE

As noted, an effective confining zone must be regional in scale and contain at least one regional geologic seal which separates the CO_2 injection zones from the surface and from USDWs. It must extend over the area of the CO_2 plume and the area where pressure is elevated such that saline water could be lifted to a USDW.

In Site Selection, confining zones identified in Site Screening are subjected to further analysis to better define their geologic characteristics in Selected Areas. This involves developing a stratigraphic and structural framework analogous to that done for the storage reservoirs and potential injection zones. The first step is to utilize the well logs that were used for analysis of the storage reservoirs. Project developers should map the tops, bases, thicknesses, and lateral extent of individual geologic seals or caprocks within the confining zone. The initial stratigraphic framework should highlight significant stratigraphic packages (e.g., sequences, unconformities, flooding surfaces, etc.) that might affect the integrity of the confining zone. The framework diagram should also and provide an understanding of the thickness and lateral extent of geologic seals within the confining zone.

The initial structural framework should highlight significant features, such as faults and folds, which can affect the integrity of the confining zone. The project developer's level of certainty in layer thickness, layer continuity, and other characteristics of geologic seal intervals within the confining zone will also impact decisions on whether to purchase or reprocess existing seismic data. In addition, details about individual confining layers may be improved by evaluating their rock properties using core samples from zones of interest.

4.1.3 TRAPPING MECHANISMS

During Site Selection, trapping mechanisms should be identified and assessed using available data for Selected Areas.

Trapping mechanisms that will further assure permanence fall into two major categories: (1) primary trapping mechanisms, comprised of low-permeability geologic features that form barriers limiting lateral flow of fluids; and (2) secondary trapping mechanisms, which may be created during fluid flow and are also effective at decreasing CO_2 mobility over distance.

Primary traps include structural traps, such as anticlines and faulted compartments; and stratigraphic traps, such as depositional pinch outs of permeable facies. Examples of these types of traps are illustrated in Figure 4.2. Figure 4.2A shows a unit of porous and permeable rock (light tan) that pinches out via stratigraphic thinning, giving way to layers of impermeable rock (dark brown); Figure 4.2B illustrates a trap formed by an anticline; and Figure 4.2C shows a sealing fault that juxtaposes impermeable strata (dark brown) above and updip of a porous and permeable sedimentary unit (tan).

Typically, the bottoms of traps are connected to extensive saline formations. If fluid is removed from the trap, it is partly or wholly replaced by water from below. Therefore, pressure is not permanently decreased in the trap. In the oil industry, this process of replacement of produced oil or gas by water is known as “water drive.” During injection, the reverse occurs, and saline water is displaced so that the pressure increase in the trap is less than it would be if there was no connection to a saline formation.

Secondary trapping mechanisms, which may be created during fluid flow, can also decrease CO_2 mobility over distance. These types of trapping mechanisms are particularly important in sites where structural or stratigraphic traps are not present. They do not impede CO_2 movement with a physical barrier, but they effectively stabilize or prevent plume migration.

One important secondary trapping mechanism is residual gas phase trapping. After injection stops, the CO_2 plume moves upward and spreads laterally, via buoyancy forces, allowing water to move in and displace some of the CO_2 that occupied pore spaces at the base of the plume. The ability of water to displace all CO_2 is limited by capillary processes, so that significant volumes of CO_2, in the range

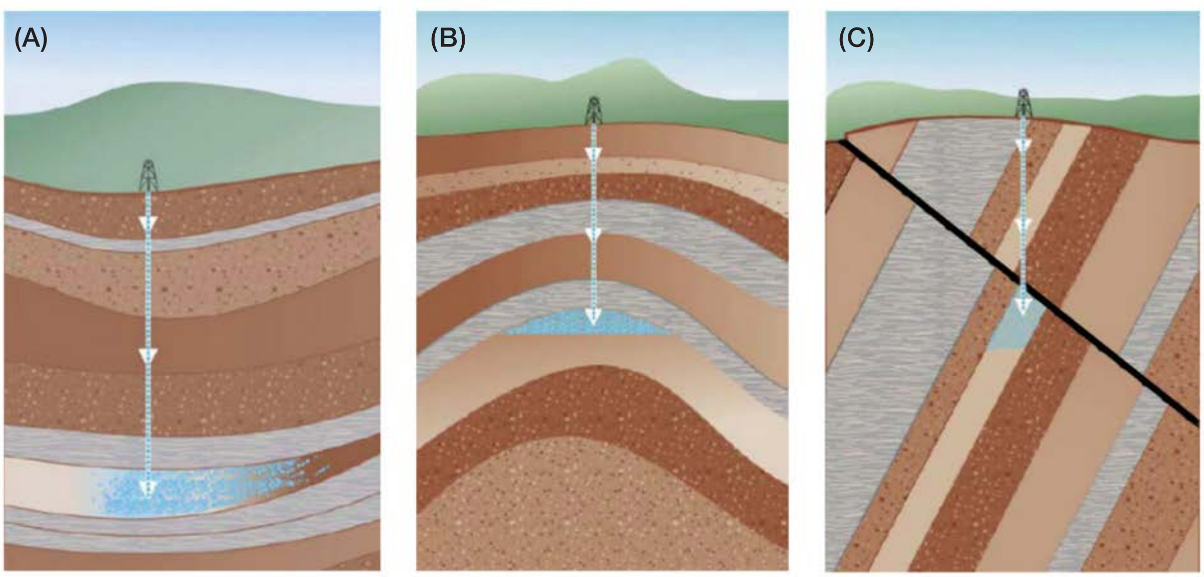

Figure 4.2: Models of Stratigraphic Trapping Resulting from Depositional Thinning of a Porous Unit (A), Structural Trapping by a Fold (B), and Trapping Against a Sealing Fault (C)

(Source: CO2CRC)

of 20 to 50 percent per unit volume of pore space, will be stranded in place as the plume thins and spreads. Such stranded CO_2 is permanently stored in the reservoir.

Two other types of secondary trapping mechanisms may form during or after injection:

1. Solubility trapping—otherwise known as dissolution trapping; some of the injected CO_2 dissolves in the saline water; the density of the saline water also increases as a result of the dissolved CO_2.

2. Mineral trapping—the CO_2 may react chemically with the surrounding rocks to form new minerals; mineral trapping can occur relatively quickly in reactive rocks, such as basalt; it occurs slowly in most sedimentary rocks.

4.1.4 POTENTIAL INJECTIVITY

Injectivity (the product of permeability times thickness) is usually reported as the rate at which fluids can be pumped into the rock without fracturing the formation. During Site Selection, an initial assessment is made of the injectivity of the candidate injection zones identified in Selected Areas. An understanding of the potential injectivity is needed for initial planning of the number of injection wells and their design (vertical, horizontal, enhanced diameter, multi-lateral, etc.), which are key cost elements in project development. During Site Selection, injectivity can be estimated using available production history data in oil or gas reservoirs, hydrologic tests (with water), or analyses of core plugs.

The maximum pressure at which injection can occur is regulated by EPA through the Underground Injection Control (UIC) Program and effectively places an upper limit on injectivity. The maximum allowable surface injection pressure (MASIP) is determined by calculating the fluid pressure in the injection zone that would fracture the injection or confining zone, propagate existing fractures, or exceed the strength of engineered features (e.g., casing burst pressure), whichever is less. MASIP is typically set at a specified fraction of the failure pressure, and it takes into consideration the density of the injectate and friction of flow though the wellbore. In later stages of site assessment, field tests of rock and fluid properties are needed to refine the estimates made during Site Selection.

4.1.5 EXISTING SEISMIC

Existing seismic data, including 2D, 3D, and passive seismic, can be used to validate the stratigraphic and structural framework in Selected Areas and interpolate between existing wells. Seismic data also can be used to help characterize the confining zone and the storage capacity of the reservoir, and to identify faulting that might produce induced seismicity upon pressurization. Consideration should be given, based on a cost/benefit analysis, to re-processing and re-interpreting the existing seismic data. Available data from naturally occurring seismicity also can be analyzed to define existing active fault locations and characteristics.

Case Study 4.4, from the MGSC Mt. Simon Sandstone evaluation, demonstrates the value of utilizing existing 2D seismic profiles for Site Selection.

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4.1.6 PROSPECTIVE STORAGE RESOURCES

Estimates of the Prospective Storage Resource, made during Site Screening, are refined based on more detailed data gathered on the structure and properties of the injection zones in Selected Areas. The refined estimates determine if the storage resource is consistent with the CO_2 management strategy established in Project Definition. At this stage, the storage resource estimate is more certain than the one developed in Site Screening and will be further refined as more data are incorporated during the life of the project. This process of refining the Prospective Storage Resource estimate is used to classify the status of the storage site and will be further discussed in Chapter 6 on Geologic Storage Resource Classification System.

Case Study 4.5, from the MRCSP Ohio project, provides an example of integrating all of the best available data to derive volumetric and production-based estimates of a Prospective Storage Resource.

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4.2 REGULATORY ANALYSIS

The second component of Site Selection involves an analysis of the potential regulatory requirements facing the project. The evaluations focus on five elements: (i) Well Classification, (ii) Corrective Action, (iii) Injection Pressure, (iv) Containment Mechanisms, and (v) Liability.

In the United States, all six classes of underground injection wells are regulated under the SDWA through the UIC Program administered by EPA. The UIC regulations are designed to protect USDWs, in the case of CO_2 geologic storage, from: plume infiltration into the USDWs; brine intrusion caused by the increased pressures from the CO_2 injection; and mobilization of any potential subsurface contaminants (i.e., trace metals and organics). The UIC Program is responsible for regulating the permitting, siting, construction, monitoring and testing, closure, and post-closure care of injection wells that place fluids (liquids, gases, semi-solids, or slurries) underground for storage or disposal (EPA, 2016a). The BPM "Operating Carbon Dioxide Storage Projects in Deep Geologic Formations" (NETL, 2016a) includes a more complete overview of the UIC Program, the description of the six well classes, and insight into UIC jurisdiction across the United States.

Case Study 4.6, from the MRCSP Development Phase project in Michigan, illustrates the importance of reviewing all regulatory requirements for existing and planned wells to ensure project objectives are achievable within the defined operational limits for the site.

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During Site Selection for any UIC well, the project developer can assess the likely well classification applicable to the type of injectate and the area of interest to determine which siting characteristics are required by the UIC Program and other state and regional agencies. This information can be obtained by reviewing regulatory language, guidance documents, and other posted information on agency websites. The owner should also directly contact regulatory entities to develop an understanding of data needs and the steps involved in the permitting process. Regulatory and permitting requirements vary from state to state. The project developer should review provisions that apply in the state where a potential project may be located. This initial review may be more helpful in identifying areas that may not meet regulatory requirements than it is in providing an indication that a project will be permitted. If this is the case, a new Selected Area should be selected. If the site appears to meet the requirements, it can continue through remaining component analysis.

At present, EPA has responsibility (primacy) for all Class VI wells. Only one state has applied for primacy (North Dakota), and that application is in review. More detailed information from EPA is available on its website at: http://epa.gov/uic/class-vi-guidance-documents.

EPA has published a guidance document (available from its website) for Site Characterization for Class VI wells. The Class VI Well Site Characterization Guidance (EPA, 2012) includes discussions about the type of data that should be collected during drilling and installation of the injection well. This may also be used as a guide for planning a stratigraphic test well, but a stratigraphic test well is not a requirement for submitting a Class VI permit application.

A Class VI permit is a staged permit. At the time a permit is issued, the owner may drill the injection well. Data collected from the well is used to update the geologic models and the Area of Review (AoR). If there are substantive changes, the owner may need to update the project plans. After reviewing the data and updated results from the injection well data, the regulatory agency may then issue the second stage of the permit to start injection.

4.2.1 WELL CLASSIFICATION

Under the UIC Program, injection wells are classified based on similarity in the fluids injected, activities, construction, injection depth, design, and operating techniques. To date, CO_2 geologic storage injection well permits have been issued under Class I, Class II, Class V, and Class VI. In 2009, EPA published regulations for a new Class VI for CO_2 geologic storage wells. This rule was promulgated in 2010. As a result, CO_2 geologic storage wells will be classified as Class II (if involving EOR) or Class VI. The Class VI requirements have significant differences from the Class II requirements. However, if a Class II well becomes a well primarily used for geologic storage, then it must meet Class VI requirements and the permit must be transitioned from Class II to Class VI. The UIC requirements are described in more detail in "Operating Carbon Dioxide Storage Projects in Deep Geologic Formations" (NETL, 2016a).

4.2.2 INJECTION PRESSURE

The siting requirements for Class VI wells under 40 CFR § 146.82 require demonstration of the presence and adequacy of injectivity based on local geologic structures, faults, and other relevant geomechanical information, plus maps and cross-sections of site lithology and USDWs. Under 40 CFR § 146.88, maximum injection pressure for Class VI wells is limited to "90 percent of the fracture pressure of the injection zone(s)." For Class II wells, 40 CFR § 146.23 limits injection pressure so as not to "initiate new fractures or propagate existing fractures in the confining zone adjacent to the USDWs." The project developer should ensure that the subsurface geologic evaluation will meet these and other the regulatory requirements likely to impact the project.

4.2.3 CORRECTIVE ACTION

UIC requirements for corrective actions for existing wells which penetrate the confining zone or reservoir within the AoR should be reviewed. For Class VI wells, the AoR is defined as the expected extent of the CO_2 plume and associated pressure front. During Site Selection, all existing wellbores in the Selected Area should be analyzed for wellbore integrity. Existing data should be evaluated and future data needs should be identified. Prior to injection, it must be shown that any known well (active or plugged) cannot serve as a conduit for fluid movement, and any deficiencies must be mitigated.

Case Study 4.7, from the MRCSP Michigan Basin Project, describes a wellbore integrity analysis that was undertaken to assess the potential for CO_2 leakage from existing wells in the study area.

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4.2.4 CONTAINMENT MECHANISMS

Class II and Class VI UIC wells require project developers to demonstrate the presence and adequacy of a containment mechanism. The demonstration must include information on local geologic structures, faults, and other relevant geomechanical information. It must also include maps and cross-sections of site lithology and USDWs. Anticipating these needs should help to streamline the permitting process and help keep a project on schedule, limiting potential scheduling delays and cost overruns.

4.2.5 LIABILITY

Liability for the CO_2 after it has been injected into the subsurface is currently being debated. Uncertainty in long-term liability and responsibility for the injected CO_2 could affect the forward progress of a project. There is currently no clearly defined, widely accepted framework for the assignment of liability in CO_2 storage, although several states have adopted or are considering legislative approaches to address the issue. For example, Montana passed legislation that places liability for CO_2 geologic storage with the CO_2 injection throughout the injection, monitoring, and verification phases. If the developer can demonstrate that all of the UIC permit and regulatory requirements for CO_2 storage have been met, the Montana Board of Oil and Gas can issue a "Certification of Completion" as early as 25 years after CO_2 injections have ended. Following the issuance of a Certification of Completion, the developer continues to be liable for the geologic storage reservoir and the stored CO_2, and must continue the required monitoring and verification activities for at least 25 years. Following the monitoring and verification period, the developer may transfer title of the reservoir and CO_2 to the state, at which point the state assumes liability for the resources. If the stored CO_2 and geologic reservoir title is not transferred, the liability of the resource remains with the developer indefinitely, with the possibility of later transfer after a review period. The Montana legislation is contingent upon Montana attaining primacy over Class VI wells from EPA. This is just one example of one state's approach to liability. Project developers must review and understand any liability statutes in states where sites are being considered. Developers may want to discuss the implications with potential financiers or internal risk officers.

Class VI rules only address liability during the period in which the Class VI permit is active. Under a Class VI permit, financial responsibility for injection well plugging, corrective action, and post-injection site care and site closure and for emergency and remedial response is required. Once the Class VI permit is closed, the financial instruments providing coverage for these areas of liability expire.

In addition to the issues discussed above, several other regulatory issues should also be considered during Site Selection:

- Local requirements for obtaining approvals or permits and which agencies are responsible for oversight of these programs
- Determinations whether there are other Federal or state regulatory programs that might impact projects located in the areas being considered
- Review of costs for obtaining permits (time and budget) based on previous experience in a region and ensuring that information is integrated into the project plan

4.3 MODEL DEVELOPMENT

During the third component of Site Selection, Model Data, initial geologic models are developed for use in later numerical simulations. Several elements should be addressed when developing an initial model for Selected Areas. These include: (i) Modeling Parameters, (ii) Data Requirements and Cost, (iii) Boundary Conditions and Uncertainty, and (iv) Existing Seismic Data. Models and numerical simulations are used to predict the movement of injected CO_2 and the magnitude and extent of pressure front(s). Modeling is used to test assumptions about the suitability of the storage reservoir to accept and retain CO_2 within the targeted injection zone. In addition, models used for sensitivity analysis are useful in assessing the importance of uncertainty in data. The stratigraphic and structural framework and the analysis of the sedimentary facies developed during the subsurface data analysis provide the subsurface understanding necessary to construct the initial models. At this stage, it is likely that the models are reasonably simple. Even analytical models can be useful. They will be further refined if a site matures to Site Characterization. During Site Selection, it is useful to determine the magnitude of the pressure front that is likely to result from injection and determine if this pressure front can be measured via available monitoring strategies. Follow-on studies can be designed to collect additional data that are important for updating models.

Mathematical models and numerical simulations (dynamic modeling) serve several important roles. They are used in evaluating the feasibility of CO_2 storage in the subsurface; designing, implementing, and analyzing field tests; and engineering and operating geologic CO_2 storage systems. Once a project is in operation, measurements gained through monitoring can be used to verify that the project is performing as predicted by models. Therefore, tracking changes between the initial and the updated model through time is critical for long-term validation.

Case Study 4.8, from the PCOR Partnership Aquistore site, is an example of using dynamic modeling of injection rate, injection pattern, reservoir pressure, and CO_2 movement for risk assessment.

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The linkage between model results and monitoring data can be complicated if monitoring, verification, and accounting (MVA) programs are not designed to assess and acquire data for the same parameters (including the timing of measurements, location, spatial scale, and resolution of measurements) that are generated from modeling outputs. It is particularly important that the MVA and modeling efforts be coordinated in the early stages of a project, when the opportunity exists to alter operations to ensure long-term storage and improve efficiency. Therefore, data management and project integration through time becomes a critical requirement of the project process. The need for coordinated efforts also makes it advantageous to define a common set of software tools to allow the exchange of working models and datasets.

Case Study 4.9, from the SWP Farnsworth Unit Project, provides an example of utilizing industry-standard software tools to coordinate data exchange and access to models among multiple working groups.

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Site Selection activities are designed to obtain the geologic and hydrologic information needed to develop a predictive dynamic model for Selected Areas. Modeling has application across all phases of a CO_2 storage project. However, activities specific to Site Selection are aimed at identifying suitable Potential Sites that have sufficient storage resource, suitable confining zones, and the capability to retain injected CO_2 over hundreds of years. Modeling results are also used to assist additional activities, including: calculation of the AoR (a requirement under UIC Class VI Well Regulations); determination of the most advantageous injection zones and injection strategies; assessment of potential leakage pathways; potential for induced seismicity; mitigation options; and risk evaluation.

4.3.1 MODELING PARAMETERS

Project developers may select or reject a Selected Area based on the results of modeling. The first tenet in developing a model is to identify the model parameters that will be used as inputs. Model type (static and dynamic) and parameters necessary to populate the models should be planned to reflect the subsurface system behavior, including injection and confining zones.

4.3.2 DATA REQUIREMENTS AND COST

Once the modeling parameters are established, the project developer should undertake careful analysis of the data and data format required to develop the model. At this point, it is important to assess the costs and benefits of acquiring additional data to reduce uncertainty in the modeling results. Generally, the more data that is acquired and incorporated into the model, the more confidence and certainty will reside in the results. However, additional data can be costly to acquire. Therefore, a project developer should determine the critical modeling parameters and the value of needed information. They should specifically consider how much and what kind of data is sufficient to lower uncertainties while keeping the project economical.

4.3.3 BOUNDARY CONDITIONS AND UNCERTAINTY

Dynamic models are used to simulate the behavior of injected CO_2 in geologic storage reservoirs. Because these reservoirs are complex, models will have a certain level of uncertainty during this stage of development. This uncertainty will decrease as a Selected Area matures, and more data are acquired. Also, it should be understood that all models bear certain capability restrictions. Project developers should evaluate the model uncertainties and restrictions against a set of acceptability confidence levels for the parameters to better understand the model outputs. Model results, uncertainty, and confidence in results should be thoroughly communicated with stakeholders, especially those who are not familiar with modeling, uncertainties, and confidence parameters developed for the model, or who are not familiar with the role of additional geologic evaluation in decreasing uncertainty.

In Case Study 4.10, also from the PCOR Aquistore Project, a geocellular model was used for estimating injectivity, pressure effects, likely CO_2 plume geometry, plume migration pathways, and overall storage suitability.

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Boundary conditions of the injection zone define whether stratigraphic or structural features limit flow on the bottom and on the sides of the model. No-flow or low-flow boundaries will increase the rate of pressure build-up and influence the size and symmetry of the plume. They are key factors in determining how long injection can continue before pressure builds regionally to limit injection rate. Examples of no- or low-flow boundaries include faults that compartmentalize the reservoir, regional facies changes that limit the extent of injectable facies, and heterogeneity such as channel geometries that limit lateral flow. The boundary conditions are identified, characterized, and evaluated during subsurface analysis. Boundary conditions may need to be simplified for incorporation into the dynamic model(s).

4.3.4 EXISTING SEISMIC DATA

During this stage of development, a model is based on stratigraphic and structural frameworks developed during the subsurface analysis. Some Selected Areas being evaluated might have existing two-dimensional (2D) or three-dimensional (3D) seismic data. Under these circumstances, available seismic data over the AoR should be considered to supplement and validate the initial models.

4.4 SITE SUITABILITY ANALYSIS

In the Site Selection process, the site suitability analysis focuses on four primary elements: (i) Infrastructure, (ii) AoR Requirements, (iii) Surface Access, and (iv) Pore Space Ownership. The purpose of the analysis is to determine if there are any local siting issues and feasible mitigating actions given the criteria established in the Project Definition. For example, even though a Selected Area may have favorable geologic and other characteristics, it may not be suitable because of infrastructure needs, pore space ownership issues, or for other reasons. These issues should be identified during Site Selection.

4.4.1 INFRASTRUCTURE

When considering the suitability of Selected Areas, infrastructure requirements for the future injection operations should be analyzed. The analysis should be based on site-specific characteristics, such as storage type, potential plume migration, and source/injection site distance. Types of infrastructure to be considered should include injection and monitoring wells, compression equipment, transport pipelines, and various types of monitoring devices.

Potentially, the most capital-intensive infrastructure costs could be transport of CO_2 to the project site. This is a major factor to consider when selecting a CO_2 geologic storage site. Carbon dioxide can be moved via truck, railroad, ship, and pipeline, although pipeline is currently the only economically feasible transport for commercial-scale projects. Consequently, CO_2 for geologic storage will nearly always be transported to the injection site by pipeline. Carbon dioxide has been transported through commercial pipelines in the United States since 1972. Currently, the CO_2 pipeline network is more than 3,600 miles in length (see Figure 4.3). The system predominantly carries naturally occurring CO_2 to oilfields for CO_2 EOR.

The ability to transport CO_2 to the site is critical to project success. Access to an existing CO_2 pipeline (particularly if it has additional capacity) may be a positive factor in selecting a particular site. If such access is not available, a pipeline will have to be constructed and the costs for building the pipeline and permitting of a pipeline ROW will have to be figured into the capital costs and schedule of the project. The distance between the CO_2 source and storage site, the injection volume, pressure, rate, and location of the pipeline ROW will influence overall pipeline design and cost.

The CO_2 pipelines are operated at ambient temperature and high pressure, with primary compressor stations located at the pipeline inlet and booster compressors located as needed along the pipeline. CO_2 pipelines are similar to natural gas pipelines, requiring the same attention to design, monitoring for leaks, and protection against overpressure, especially in populated areas (IPCC, 2005). See Appendix 2 for details on pipeline regulations and ROWs.

4.4.2 AREA OF REVIEW (AoR) REQUIREMENTS

During Site Selection, developers should estimate the AoR and assess potential surface and pore space ownership issues. Class VI well regulations require developers to calculate the AoR using sophisticated computational models. During Site Selection, developers may use a range of methods to estimate the AoR in Selected Areas (see Risk Management and Simulation for Geologic Storage of CO_2 [NETL, 2016b]).

4.4.3 SURFACE ACCESS TO DEVELOP CO_2 INFRASTRUCTURE

The ability to gain surface access should be considered in the site suitability analysis. Factors that should be considered in the analysis include: the location of geologic storage sites in relation to CO_2 emissions sources, competing land uses, impact on environmentally sensitive areas, and availability of infrastructure.

In Case Study 4.11, from the MRCSP Development Phase Project, existing infrastructure, including wells and pipelines, allowed the project to save significant time and resources.

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Considerations should also be given to geographic terrain and population density, which may restrict access for drilling and characterization activities. Permission must be obtained from surface property owners for acquisition of seismic survey data. Surface easements for pipelines and injection facilities will be necessary for operation of a large-scale CO_2 geologic storage project. For CO_2 pipelines, surface and near-surface competition may come from other industries that require the same zoning, easements, and ROWs. This may include utility transmission lines, oil and natural gas pipelines, water pipelines, fiber optic lines, and sewers. There may also be roads, rivers, and railroads requiring special easements or ROWs. Proper planning is necessary to address these potential issues with surface access.

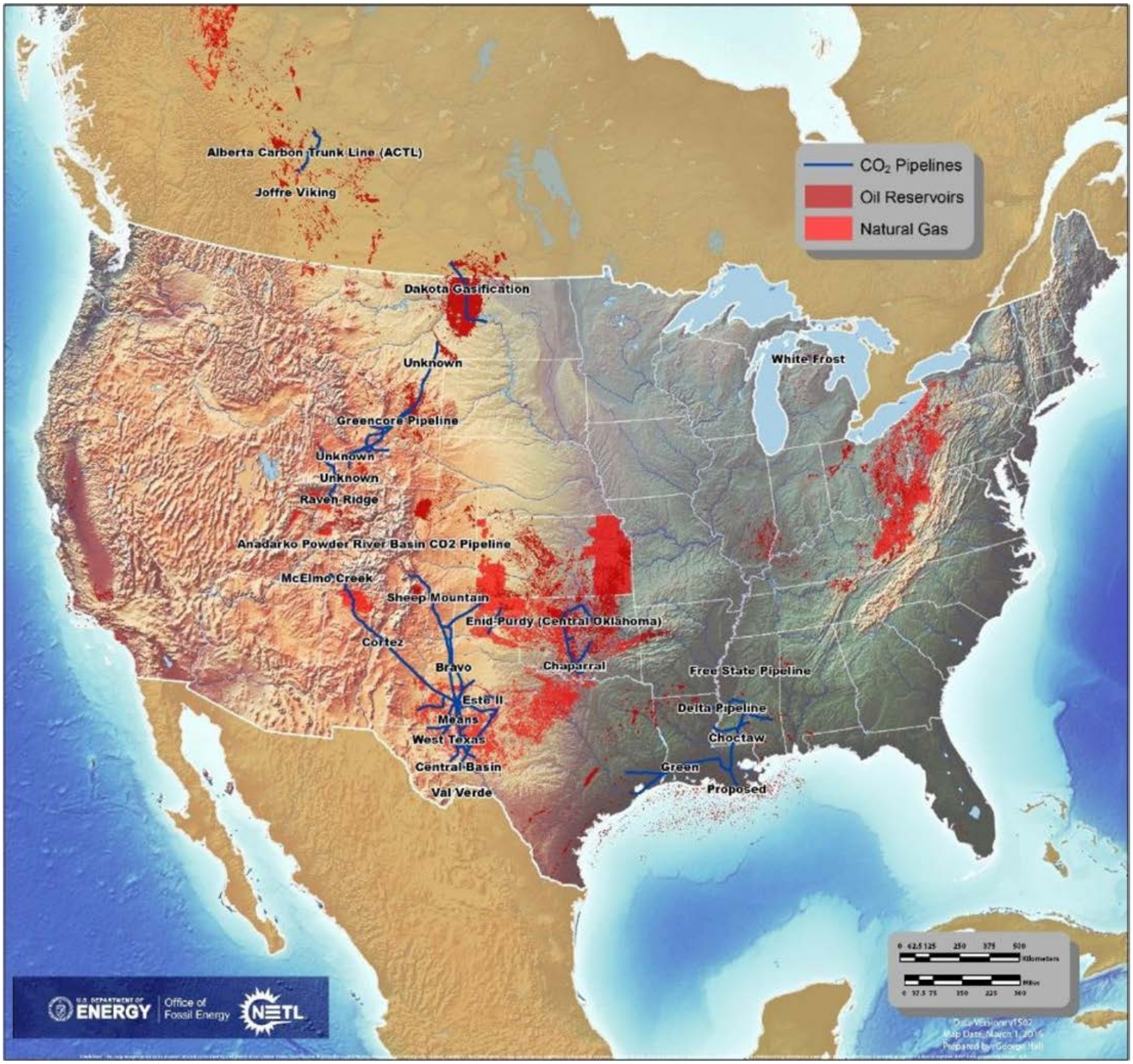

Figure 4.3: Existing CO_2 Pipelines (blue) with Oil and Natural Gas Fields (red)

(NATCARB, 2016)

CO_2 injection wells may also compete with subsurface uses such as mineral extraction and other underground injection applications. Mineral extraction includes oil and natural gas production, solution mining for salt or uranium, and coal and mineral mining. Coal, oil, and natural gas companies often hold leases on marginally economic prospects in case the commodity price escalates. In these cases, surface access may be denied until the leases expire.

4.4.4 PORE SPACE OWNERSHIP

The fourth element to be addressed in the site suitability analysis is pore space ownership and ownership of the injected CO_2. The jurisdiction for pore space ownership resides with the states. However, the legal treatment of pore space at the state level varies significantly. The project developer should have an early understanding of the state rules that govern the areas being considered for CCS in the Site Selection stage. Using modeling results to assess the extent of the predicted subsurface CO_2 movement and associated pressure front, the developer can begin to determine how many pore space owners may be affected and potential implications for project costs.

Most states have not yet passed legislation that specifically addresses pore space ownership. However, case law generally supports surface estate ownership of pore space. This concept is consistent with the legal framework governing subsurface mineral rights. There are currently four states with legislation that appears to be converging on a consistent model that vests ownership of the subsurface pore space to the surface owners above the storage space, unless the pore space has been previously severed from the surface estate or expressly conveyed to a different owner. Wyoming adopted this approach in legislation enacted in 2008, pursuant to House Bill 89. The following year, Montana and North Dakota adopted similar legislation under Montana Senate Bill 498 and North Dakota Senate Bill 2139. In 2011, Oklahoma followed suit and defined the pore space as a property right owned by the surface owner under Title 60 of Oklahoma Statutes, Section 6. It is important for project developers to understand that while most states appear to grant pore space rights to the surface estate owner, there are instances where case law granted pore space rights to the mineral owner. This emphasizes the need to fully understand the state's established legal approach toward pore space ownership while investigating Selected Areas for storage projects.

4.5 PRELIMINARY SOCIAL CHARACTERIZATION

Social characterization is an important part of Site Selection because it involves more direct investigation into the socio-cultural factors that could influence how the project is viewed in Selected Areas of interest. The element for this evaluation requires the project developer to gather and assess social data. The community assessment should be used to frame an outreach plan. The evaluation begins with readily accessible information such as local media and websites. In certain communities, data gathering could involve more direct contact through interviews with key stakeholders, use of focus groups, and other community discussions. At this stage, it may also be useful to initiate discussions with regulators or other officials. Once all the pertinent information is collected, information can be used to assess the potential benefits to the community, account for potential concerns that will need to be addressed through project design, and identify aspects that will need to be considered in an outreach plan (see the Public Outreach and Education for Geological Storage of Carbon Dioxide Projects BPM [NETL, 2016f]).

4.5.1 GATHERING AND ASSESSING SOCIAL DATA

At this stage, data collection focuses on a specific set of potential communities within the most promising Selected Areas. If conditions warrant, more intensive research might be initiated focusing on a review of the stated positions and official records of relevant regulatory and elected officials. The exercise will yield a better understanding of their familiarity with the scientific concepts in CO_2 geologic storage, and their stated positions on development and community growth. Securing an understanding of land ownership structures is important. Examples of questions to be answered include:

- What kind of land use exists directly adjacent to the Selected Area?
- Is it residential, industrial, or agricultural?
- If residential, is it densely populated?
- If there are current land uses in practice, such as mining or natural gas activities, what companies are involved and what is their local history?

- Does the community have a strong local government and/or business development community?
- Do those groups have stated positions on economic development, environmental protection, climate change, or other issues that might influence perceptions of a carbon storage project?
- Are there other concerns, such as increased road traffic from future operations, effects of noise from operations on their livestock, etc.?

Case Study 4.12, from the SWP Farnsworth Unit Project, illustrates some of the benefits of working with industry partners, who are already working in the area and are familiar with the social context and potential issues the project may face.

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If appropriate, a project team can begin preliminary discussions or interviews with key stakeholders to learn more about the community and to begin sharing information about geologic storage. At this time, focus group interviews may be useful to develop a better understanding of community views on related issues. If there are a dozen Selected Areas, the main effort may be on identifying key areas of potential concern or benefit. If the list of areas is narrowed to a few, then more intensive research might be warranted. Social characterization is described in the Public Outreach and Education for Geological Storage of Carbon Dioxide Projects BPM (NETL, 2016f).

4.6 QUALIFICATION OF SITE FOR INITIAL CHARACTERIZATION

The Site Selection process, as illustrated in Figure 4.1, results in a list of candidate Potential Sites. Before being advanced to Site Characterization, each site must first undergo three additional evaluations: (i) Frame Site Characterization Plan; (ii) Frame Site Development Plan; and (iii) Evaluate Economic Feasibility.

4.6.1 FRAMING SITE CHARACTERIZATION PLAN

A Site Characterization plan should be outlined for all candidate Potential Sites and should address the components needed to understand every aspect of the site. These components include: (1) Public Outreach Needs; (2) Regulatory Requirements; (3) Reservoir Framework Data; (4) Modeling Data; and (5) Site Development Needs. The Site Characterization Plan should outline activities and data needs, analytical and modeling strategies, and regulatory review needed to determine whether a site has all the characteristics of a Qualified Site.

4.6.2 FRAMING SITE DEVELOPMENT PLAN

A preliminary site development plan should be outlined for all candidate Potential Sites being considered for advancement to Site Characterization. This plan should take into consideration various project parameters, including anticipated delivered volumes of CO_2, transportation infrastructure, surface equipment for injection and monitoring, estimated number of wells, well construction, estimated size of surface footprint of the project, and anticipated operational time. The plan should also address contingency plans for site interruption or shutdown, which could include a spare injection-ready site for operation reliability.

4.6.3 EVALUATING ECONOMIC FEASIBILITY

The preliminary site development plan should be used to conduct an initial economic analysis of each candidate site to determine if the site can meet the project's economic hurdles established during Project Definition. Each site development plan should be weighed and ranked for economic feasibility. The site that best meets all criteria with the most favorable economics should be the first site elevated to Site Characterization.

4.7 RCSP CASE STUDIES

CASE STUDY 4.1 — **SECARB**

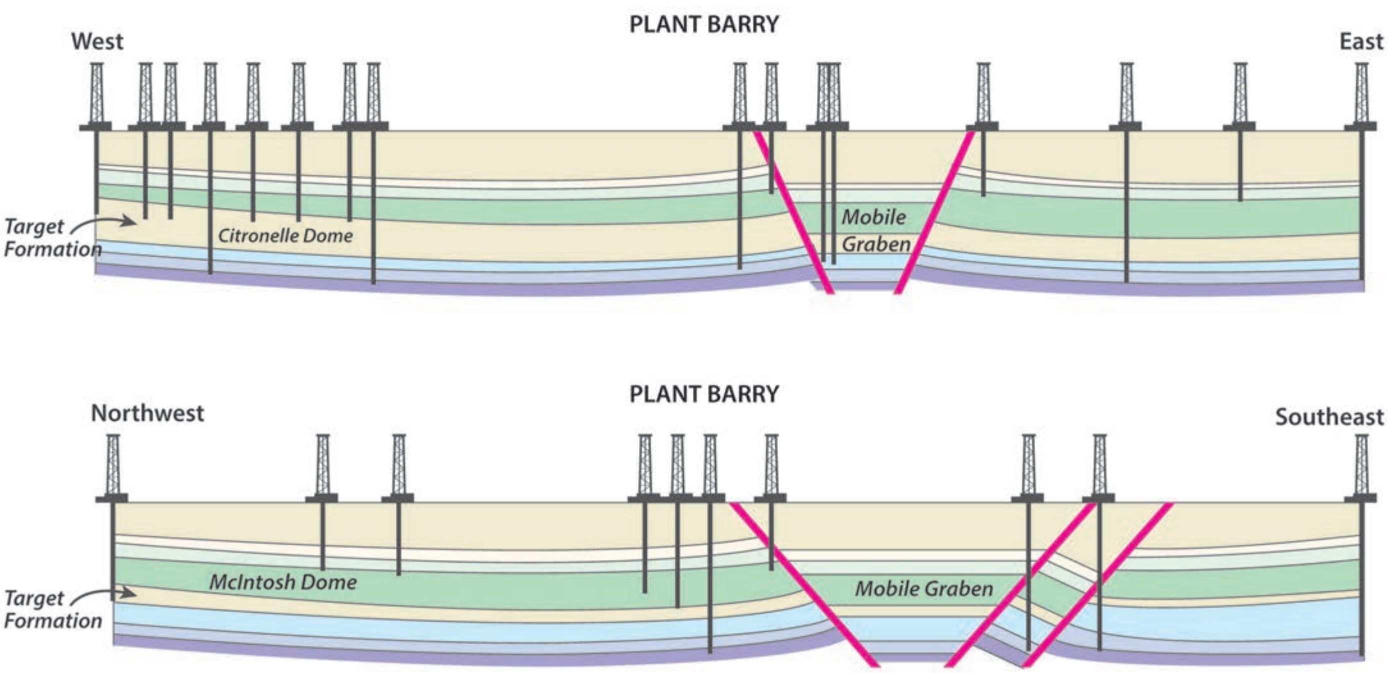
SOUTHEAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (SECARB)

Formation Evaluation – Development Phase "Anthropogenic Test" Site Selection

The Southeast Regional Carbon Sequestration Partnership (SECARB) Development Phase "Anthropogenic Test" is an integrated demonstration of CO_2 capture from a coal-fired power station, and the subsequent transportation, sub-surface injection, storage, and monitoring of the captured CO_2. Alabama Power's Plant Barry, a 2,657-MW coal and natural gas-fired power plant located near the town of Bucks, Alabama, provided the source of CO_2. Plant Barry lies along the eastern margin of the Mississippi Interior Salt Basin, where numerous saline reservoirs have significant sequestration potential.

Initial site characterizations beneath the plant's property suggested that ample porous and permeable sedimentary Gulf Coast strata capable of accepting the project's target injection volumes were present. However, well control beneath the plant was insufficient to define the geologic structure. The successive construction of regional structure maps from available data revealed that the plant site posed a leakage risk in that CO_2 injected beneath the plant site would likely migrate up dip towards the western edge of the Mobile Graben and a large associated fault (see figure below).

A key decision was made by the project team to re-locate the storage site to the nearby Citronelle Dome, a giant, salt-cored anticline located approximately 12 miles west of Plant Barry. Geologic studies of the Citronelle Dome indicated that the site contained multiple porous and permeable saline reservoirs capped by up to 2,000 feet of impermeable chalk and marine shale and, most importantly, structural closure in all directions (Esposito, et. al., 2008). Citing these major lines of evidence, the Citronelle Dome (SECARB Citronelle Project) can be considered a major and safe geologic sink for anthropogenic CO_2.



Structural cross-sections showing Mobile Graben and Citronelle Dome near Plant Barry

(Adapted from Esposito et al 2008).

CASE STUDY 4.2 — **BSCSP**

BIG SKY CARBON SEQUESTRATION PARTNERSHIP (BSCSP)

Carefully Review Data when Transitioning from Site Screening to Site Selection and Identify Areas of Uncertainty

Site screening, following the methodologies outlined by the National Carbon Sequestration Database and Geographic Information System (NATCARB) and Section 3 of this BPM, is useful for exploring regional storage opportunities. However, at the screening stage, operators must consider the cost and time required to thoroughly review existing datasets. Sites that graduate to the selection phase should be further assessed with greater attention to the quality and accuracy of data feeding the selection criteria. Publically available datasets provide a wealth of information for initial screening, but electronic databases are often built upon poorly documented or inaccurate reports and are subject to translational errors in the conversion from print to digital format. These errors may be considered negligible at the site screening level, but could have significant impact on the estimated permitting and operational costs, injectivity models, and project design, which are assessed during site selection. Perpetuating errors through to the site characterization step may lead to costly delays or an inability to carry out the project.

The Big Sky Carbon Sequestration Partnership's (BSCSP) Kevin Dome Project site is undeveloped and data-poor compared to other projects injecting into mature oil and gas fields. Existing geologic interpretations of the area showed promising conditions for both CO_2 production from the gas cap and injection into the water leg. However, well data for the zones of interest was limited. During the screening process, the site met basic subsurface geology criteria, such as an injection formation deeper than 800 meters and a thick anhydrite caprock to trap CO_2. It also met social and surface characteristics amenable to carbon storage operations, including low population density and a history of oil and gas exploration in the area at more shallow depths. As the project transitioned to the site selection phase, deeper investigation of the available databases indicated that most of the wells penetrating the target zones were drilled prior to modern log suites, and formation testing results were often poorly documented. Being near the Canadian border, formation nomenclature was variable, and records of well locations and plugging status were inconsistent. Data for several wells obtained during site screening from available databases proved to be inaccurate upon further review, most commonly because of the conversion of location legal descriptions to geospatial coordinates. These inaccuracies, especially as pertaining to old wells at Kevin Dome, had significant implications for the UIC Class VI Area of Review and associated remediation costs. Poor or inaccurate testing records for even a couple wells can skew assessments when there is a low number of wells penetrating the formations of interest. Documentation of inaccuracies and communication of data limitations to project managers is essential when selecting a site for further development. Recognizing the limitations of site data early in the characterization process allows for the identification of cost-effective methods to reduce uncertainty and fully evaluate the site's viability for carbon storage.

CASE STUDY 4.3 — **PCOR**

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP

Using Outcrop Data to Provide Insight into Subsurface Regional Structure, Facies, and Heterogeneities – An Example from the Bell Creek Oilfield

Understanding the complex nature of the subsurface to characterize a reservoir for potential CO_2 storage is a challenging task because of the limited access to deeply buried rock formations. However, data collected from the same formation at outcrop locations can provide insight into understanding regional structure, facies, and heterogeneities, which can then be correlated to core and used to improve 3D geologic models.

Examination of outcrop to gain understanding of the equivalent subsurface reservoir rock.

As part of its investigation into the associated storage of CO_2 which occurs as part of an active CO_2-EOR project, the Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), conducted several field trips to a Cretaceous Muddy (Newcastle) Formation outcrop in Wyoming, which is analogous to the nearby (25 miles) Bell Creek oilfield reservoir. The proximity of these outcrops to their deeply buried (approximately 4,500 feet) equivalents in the Bell Creek oilfield provided an excellent opportunity to understand the potential heterogeneities in the reservoir system.

Although numerous wells and core are available in the field, many cores had poor recovery, resulting in only 25 cores to interpret vertical and horizontal variations in facies and internal structure. Because of the small number of core, there are subtleties in the 3D geologic model framework that occur at a finer resolution than the well control. Outcrop examination provided a source of extensive geologic data in the X, Y, and Z directions, important in gaining an understanding of regional structure and geologic heterogeneities.

The investigation showed good sedimentological correlation between outcrop and subsurface core. Three formations and five facies were described from the subsurface core, and the same three formations and four of the five facies were seen in the outcrop. Similarities between the corresponding surface and subsurface facies allowed further lab testing on analogous outcrop rock when sufficient subsurface core was unavailable. Data collected from the outcrop provided insight for major variogram ranges, porosity-to-permeability transforms, geomechanical variables, and definition of flow zones and barriers. The data also helped minimize uncertainty while developing the associated 3D geologic models.

CASE STUDY 4.4 — **MGSC**

MIDWEST GEOLOGICAL SEQUESTRATION CONSORTIUM (MGSC)

Understanding the Geology – Using Long 2D Surface Seismic Profiles for Site Evaluation in the Cambrian Mt. Simon Sandstone

The Midwest Geological Sequestration Consortium (MGSC) evaluated the importance of using long 2D surface seismic profiles for site evaluation of the Cambrian Mt. Simon Sandstone. Figure A shows an example of a possible fault that penetrates through the B. Knox, which is equivalent to the top of Eau Claire Shale and is the primary seal for the Mt. Simon Sandstone, the Maquoketa (the secondary seal), and New Albany Shale (the tertiary seal). This particular fault is located approximately 30 miles from the Illinois Basin—Decatur Project (IBDP)—and is significant because it had not been previously observed. Faults that penetrate seals form potential leakage pathways so CO2 sequestration projects involving Cambrian strata should not be located near these structural features. There is also a higher risk for induced seismicity in areas of faulting.

Some of the faulting appears to occur contemporaneously with Mt. Simon Sandstone deposition but do not penetrate the seals. These types of faults are important because the Mt. Simon Sandstone is thinner on the up-thrown side compared to the down-thrown side of the fault. Therefore, there is less Mt. Simon reservoir on the down-thrown portion. Figure B shows a fault interpretation dipping to the east with a thickening of the lower Mt. Simon interval. This fault set is adjacent to a Precambrian paleotopographic high similar to numerous others documented within the Illinois Basin (Leetaru and McBride, 2009). Other long Illinois seismic profiles have found Precambrian paleotopographic highs. Knowledge of where these basement highs occur is an important factor in selecting a CO_2 injection well location. Preferably, a proposed injection well location would be away from the basement high into a thicker section of the Mt. Simon Sandstone.

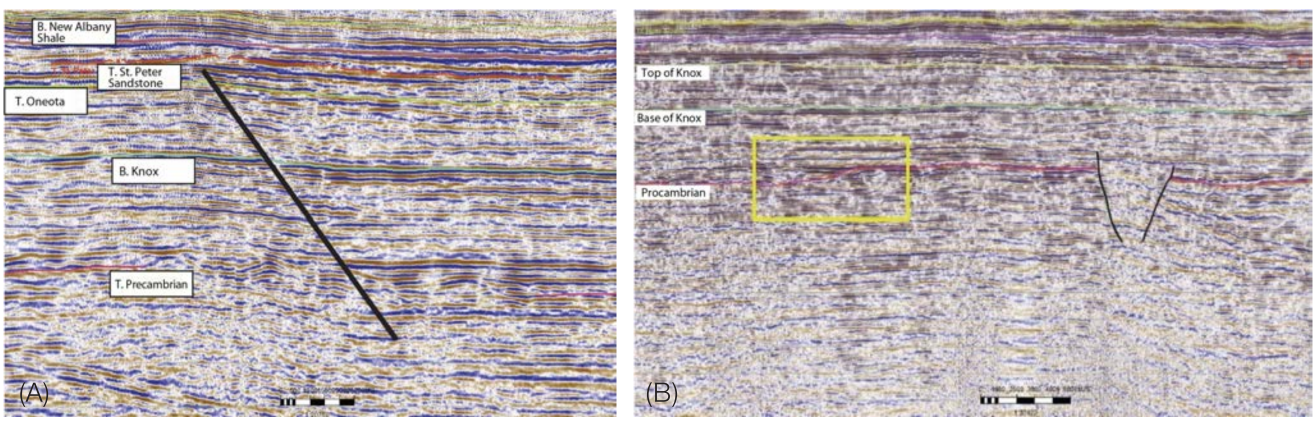


Figure A (left): The black line is interpreted to be a possible fault that could penetrate the entire Mt. Simon Sandstone, Eau Claire, the Maquoketa Shale, and potentially the New Albany Shale. The T. Precambrian correlation is not continuous due to correlation issues. Figure B (right): An example of contemporaneous faulting during deposition of the Mt. Simon Sandstone is shown by the black lines. The yellow box highlights a Precambrian paleotopographic high.

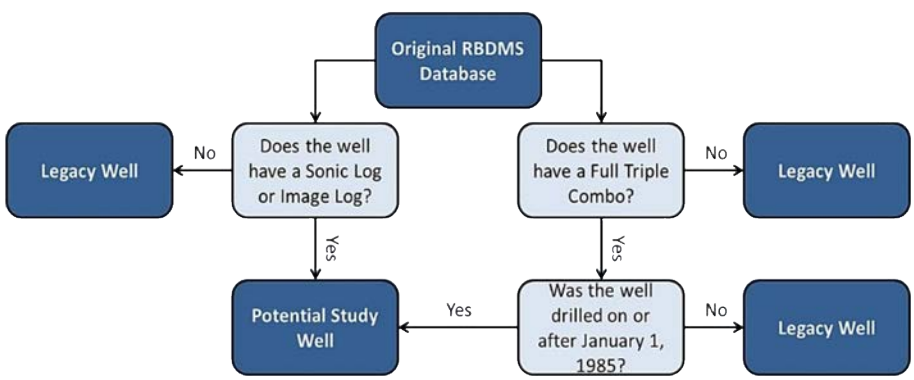
CASE STUDY 4.5 — **MRCSP**

MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

Integrating Best Available Data to Model Prospective Storage Resources: An MRCSP Example

The Midwest Regional Carbon Sequestration Partnership (MRCSP) participated in an Ohio Coal Development Office project to provide an expanded assessment of CO_2-EOR and CO_2 storage opportunities in Ohio. Battelle developed geologic framework models for "reference" reservoirs in the Clinton and Knox formations by integrating the best available data from well logs, core analysis, seismic data, fracture data, and production history. The geologic framework models and production history assessment were then used to derive volumetric and production-based prospective storage resource estimates.

A list of available logs for the East Canton and Morrow Consolidated oilfields (ECOF and MCOF, respectively) was obtained from the Risk-Based Data Management System (RBDMS), a database of oil and gas well information for more than 240,000 drilled and permitted wells in the state of Ohio that is maintained by the Ohio Department of Natural Resources (ODNR), Division of Oil and Gas (ODNR, 2013a). This resource, along with personal correspondence with the ODNR Division of the Geological Survey staff, was used to determine the availability of logs for wells in the ECOF and MCOF. The quality assurance/quality control (QA/QC) and filtering process of data for prospective storage resource estimation for the two fields is shown in the figure below. Full triple-combo logs were treated as the minimum amount of data required for a well to be considered for further study. For wells with triple-combo logs, only those drilled on or after 1985 were selected. Every well with a sonic or image log was kept in the query, regardless of drill date, due to the rarity of advanced logs. Well logs with substantially segmented data, irregular log curves, anomalous data spikes, or incomplete logs through the formations of interest were eliminated from the subsequent assessment. Logs retained after the QA/QC process were incorporated into the Petra® software database, a geologic data management and analysis tool, for further analysis for the ECOF and MCOF wells. Production history data was obtained from the Tertiary Oil Recovery Information System (TORIS) database, the Production of Oil and Gas (POGO) in Ohio database (ODNR, 2013b), and the RBDMS database. The TORIS database contains field-wide information such as porosity, oil gravity, original oil in place (OOIP), cumulative production, etc. The POGO database contains well-specific oil, gas, and brine water production data from more than 80,000 individual wells in Ohio. With more than 240,000 entries, the RBDMS is the most comprehensive list of oil and gas wells in Ohio. Core descriptions and all available porosity/permeability core data for the two formations of interest were also acquired from ODNR for incorporation into geologic framework models and storage resource estimates.



Process for selecting wells for further study and development of geologic framework models.

CASE STUDY 4.6 — **MRCSP**

MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

Ensuring Project Objectives and Operational Parameters are Aligned with Regulatory Requirements

As part of the regulatory analysis for the Midwest Regional Carbon Sequestration Partnership (MRCSP) Development Phase project in Michigan, both existing and planned permits for Class II wells were reviewed to ensure that the regulatory requirements are consistent with the MRCSP scientific objectives. This review concluded that the targeted injection and storage rates of the project should be achievable within the operational limits defined by regulatory requirements described below.

The MRCSP project was designed to leverage existing UIC Class II permits and EOR infrastructure to achieve the project goals with no anticipated environmental impact. The project did not involve any significant new construction activities, nor did it involve major changes in facilities missions and operations, changes in land use, or regulatory permit requirements. Furthermore, public outreach and concerns associated with this project were minimal because the proposed project was closely integrated with "business-as-usual" oilfield operations that have been ongoing since the mid-1970s.

Injection is conducted under a UIC permit implemented by the EPA Region 5 UIC Program. The permit, which is held by Core Energy, LLC, requires review by EPA Region 5 every five years from the last effective date. Furthermore, reports documenting any new well workover, logging, or well testing must be reported to EPA Region 5 within 60 days of completion of the activity. After a workover is done, EPA Region 5 must give authorization to commence injection prior to injection activities.

In the main test reef, the injection well was authorized for injection of CO_2 into the A-1 carbonate of the Salina Group and the Niagaran Group at depths between 5,302 and 5,678 feet. The permit required mechanical integrity testing of the well every five years. The permit established the operating limits as well as monitoring and reporting requirements (see table below). Reporting and record keeping was completed by Core Energy, LLC. As with any UIC permit, any significant variance to proper operation and maintenance of the injection system requires notification of the EPA and, if needed, mitigation measures.

Minimum Operating, Monitoring, and Reporting Requirements Under the UIC Permit

Characteristic	Operating Limits	Monitoring		Reporting
		Frequency	Type	Frequency
Injection Pressure Maximum	1,818 psi	Weekly	––	Monthly
Annulus Pressure	––	Weekly	––	Monthly
Flow Rate	––	Weekly	––	Monthly
Cumulative Volume	––	Weekly	––	Monthly
Annulus Liquid Loss	––	Quarterly	––	Quarterly
Chemical Composition of Injectate	––	Annually	Grab	Annually

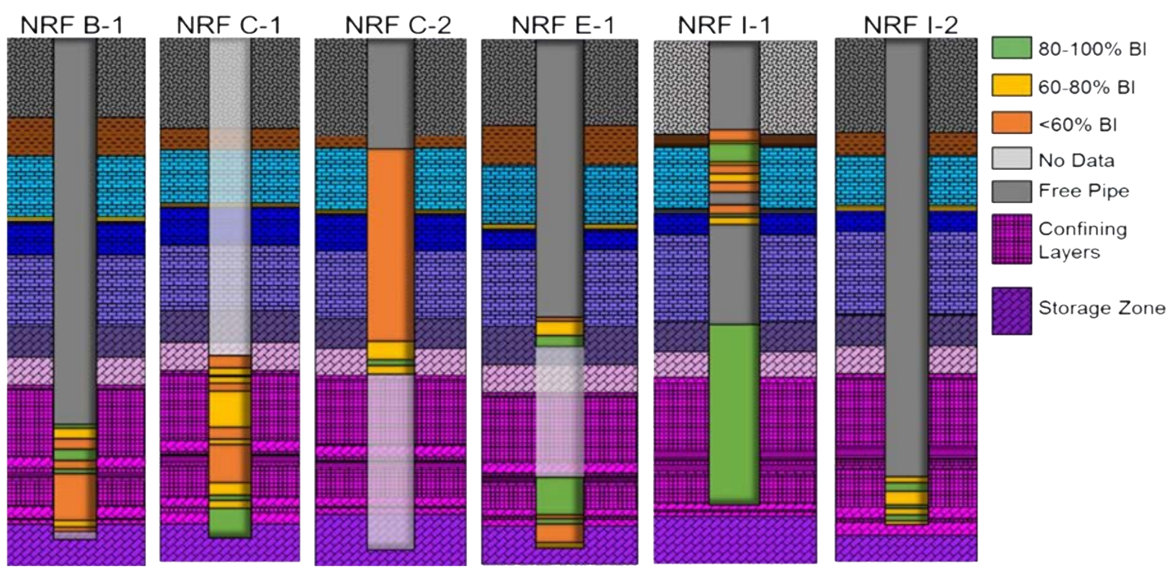
CASE STUDY 4.7 — **MRCSP**

MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

Incorporating Well Integrity Analysis in Site Screening and Selection to Help Define CO_2 Leakage Potential and Determine Corrective Actions

A wellbore integrity analysis for wells on and near the Midwest Regional Carbon Sequestration Partnership (MRCSP) Michigan Basin Project was conducted following a methodology developed under the DOE-funded Wellbore Integrity Project. The analysis characterized the condition of existing wells in the study area to assess potential for CO_2 leakage. Oil and gas well records for the reefs encompassed by the program area were collected in three categories: (1) well construction and status information, (2) plugging and abandonment details, and (3) cement bond logs. This dataset included more than 2,500 items related to wellbore construction in the study area. The following factors in the well construction database were used for the analysis: well depth (does the well penetrate a confining layer), well completion date, well status (plugged, producing, etc.), and spatial density (the number of wells per square kilometer). In addition, the plugging database housed information on the number of plugs (including bridge plugs), thickness of plugs, and the locations of plugs relative to low-permeability formations. The analysis also involved evaluating cement bond logs to identify bond intervals, bond quality, and cement issues.

A total of 1,379 unique well locations were listed, of which 308 (22 percent) were listed as plugged and abandoned. The plugging details were manually reviewed and compiled from well permit files. Cement bond logs (CBLs) for active wells were also reviewed. Of the 21 CBLs available in the study area, only six pertained to wells directly on the reefs. The logs were reviewed with a systematic cement bond evaluation tool to assess the quantity and quality of cement in the well. A review of the data indicated that the footage of good cement quality was sufficient to mitigate leakage risk in accordance with industry standards (see figure below). This due diligence provided additional confidence in the geologic security of the reefs.



Results of wellbore integrity evaluation using the CBL standard evaluation tool.

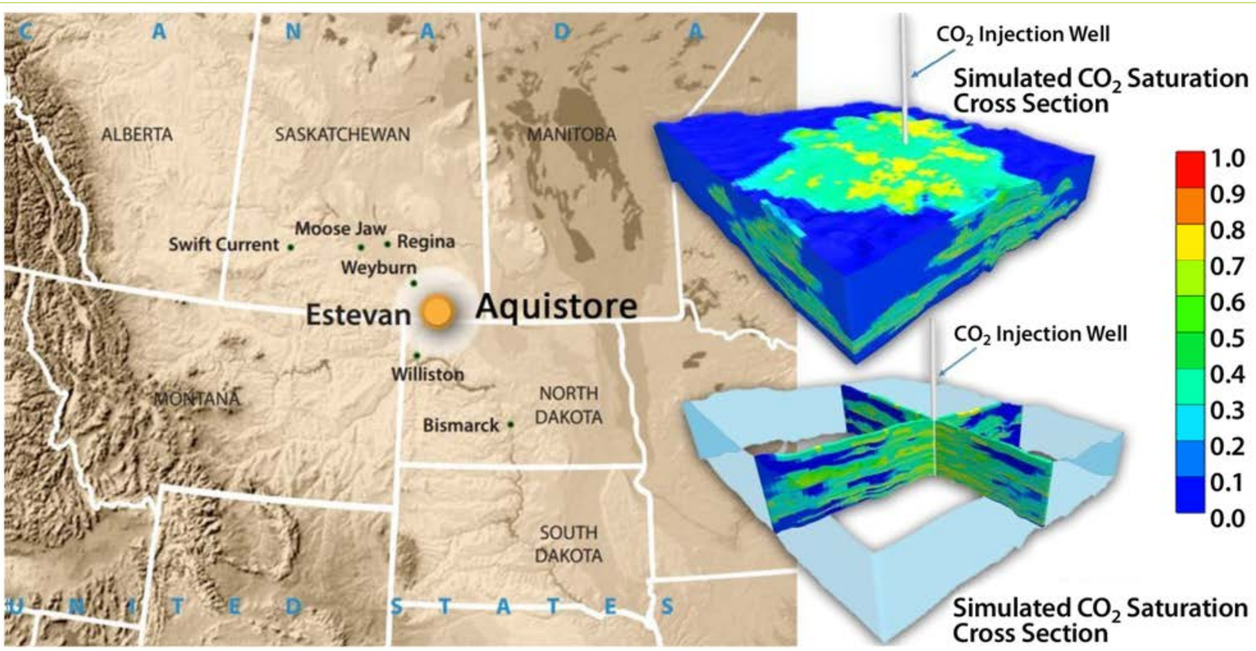
CASE STUDY 4.8 — **PCOR**

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP

The Significance of Dynamic Modeling for Refining Storage Capacity, Assessing Risk, and Addressing Permit Requirements – An Example from the Aquistore

The evaluation of a candidate saline system for its viability as a CO_2 storage horizon includes a determination of its effective CO_2 storage resource potential. This determination is based initially on the results of a static geocellular model. However, static storage resource calculations do not consider the effect of dynamic factors such as injection rate, injection pattern, timing of injection, reservoir pressure buildup, and CO_2 movement for risk assessment. In addition, EPA UIC regulations for a Class VI well requires knowledge of the CO_2 pressure plume morphology and extent from the injection well to establish an area of review for permitting purposes. Dynamic simulation (also referred to as numerical simulation) is a method that can validate the estimates of effective storage resource potential of deep saline formations by addressing dynamic factors and helping predict CO_2 movement during injection.

The Plains CO_2 Reduction (PCOR) Partnership employed dynamic simulation to determine an area of review for the Petroleum Technology Research Center's (PTRC) Aquistore site in southern Saskatchewan, Canada. A previously developed geocellular model was converted to a dynamic model and necessary parameters such as fluid composition and viscosity, relative permeability, rock and fluid compressibility, and injection volumes and rates were incorporated. Multiple predictive simulation cases were run to assess project risk by simulating the reservoir performance during CO_2 injection and post-injection. Aside from determining plume morphology and extent, the simulations were useful in providing an initial look at the effectiveness of different potential injection schemes. The simulations also helped determine how the geology affected fluid flow, pressure response, seal containment effectiveness, and potential CO_2 storage capacity. Although the Aquistore site does not fall under the purview of EPA regulations, the approach taken at Aquistore is directly applicable to any efforts that may take place in the U.S.



Carbon dioxide saturation within the CO_2 injection plume resulting from a simulated 50-year injection scenario (37 Mt) at the PTRC Aquistore site. The model grid is nearly square with sides approximately 3.5 miles in length.

CASE STUDY 4.9 — **SWP**

SOUTHWEST REGIONAL PARTNERSHIP ON CARBON SEQUESTRATION (SWP)

Using Existing Industry-Standard Software for a Characterization Framework

In the Farnsworth Unit Project, multiple groups in different locations working on facets of characterization, simulation, and other related topics, it was useful to have a common set of software tools to allow the exchange of working models and datasets. Software tools should be available to all personnel who need to share data in the project. It is best if common, industry-standard software packages are used. This allows leveraging of knowledge from software providers that focuses on enhancing the user experience. Project personnel can focus on interpretation rather than working on issues relating to data conversions from one format to another. The Southwest Regional Partnership on Carbon Sequestration (SWP) took this a step further and partnered with Schlumberger, the provider of the geologic characterization framework software (Petrel). SWP benefited from their familiarity with the software. Their expertise and involvement enabled researchers to accomplish tasks more quickly, and sharing project data between research groups, such as log studies, geologic interpretations, seismic interpretations, and simulation models. The process was simplified because of the common data formats. A few other software packages have been used to fill niches that are not as well covered by Petrel. For example, ESRI's ArcGIS family of products has been used to create a geospatial database for mapping and analysis of surface features because such data did not easily fit into the Petrel framework.

CASE STUDY 4.10 — **PCOR**

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP

Constructing a Geocellular Model for Determining CO_2 Storage Resource—An Example from the Aquistore Project

The Plains CO_2 Reduction (PCOR) Partnership, through the Energy & Environmental Research Center (EERC), in collaboration with the Petroleum Technology Research Center (PTRC), constructed a geocellular model of the target saline system for the Aquistore project. The geocellular model serves a dual purpose of determining the static CO_2 storage resource of the reservoir, and forms the basis for a reservoir simulation model to determine injectivity and dynamic storage resource. The general workflow processes described below are routinely used by the PCOR Partnership modeling team when assessing new candidate sites for CO_2 storage suitability.

The workflow for geocellular model development and optimization included petrophysical log analysis, stratigraphic correlation, structural analysis, petrophysical modeling, uncertainty analysis, and upscaling. Activities associated with the petrophysical analysis included log quality control, gamma ray normalization, calculation of both shale volume and total porosity, and a quality check of the results in comparison to the core results. To further characterize the target reservoir system, the shale volume derived by the petrophysical analysis was used to divide the model into 12 traceable zones, including six sand units and six shale units throughout the study area. The sand packages, with occasional silt and carbonate stringers, are the reservoir zones with high total porosity and low shale volumes. These zones are widespread, forming distinct, correlative units over the study area. Subdividing the reservoir system into these zones helps distribute the petrophysical properties accurately and better define the vertical and lateral heterogeneity of the model.

Total porosity and shale volume were stochastically populated throughout the model, with each zone using the upscaled logs and variogram ranges determined through data analysis. Effective porosity was then calculated for each cell, and permeability was populated based on its empirical relationship with porosity. The model was populated with additional reservoir properties, including pressure and temperature, which are necessary for calculating CO_2 density at reservoir conditions and as inputs for the dynamic simulation model.

An uncertainty analysis was performed to optimize the model and investigate the uncertainty related to specific model-building parameters, including shale porosity, variogram range, structural interpolation, and net-to-gross reservoir. The results of the uncertainty analysis were ranked accordingly by calculated pore volume, resulting in a low-, mid-, and high-volumetric case for the amount of pore volume accessible to store the potential injected CO_2. The selected mid-volume case used data for model optimization within the area where the 3D seismic survey was conducted.

A wide variety of geologically related data (e.g., geophysical, petrophysical, structural) are needed to accurately construct and populate geocellular models with an accuracy needed to confidently select or reject potential sites based on potential CO_2 storage resource. Such models also provide stakeholders with invaluable insight regarding injectivity, pressure effects, containment, and likely CO_2 plume geometry and migration pathways.

CASE STUDY 4.11 — **MRCSP**

MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

Using Existing Infrastructure and Landowner Relations

An existing CO_2-EOR operation in Otsego County, Michigan, was selected for the Midwest Regional Carbon Sequestration Partnership (MRCSP) Development Phase project partly because of a significant amount of infrastructure available for testing approaches for CO_2 injection, modeling, and monitoring within existing EOR operations. Additionally, working with an experienced operator who had strong community relationships played an important role in selecting the project location. For example, over the past 40 years, 12 wells have been drilled in or near the depleted oil field that served as the main test field for the project. That history suggested landowner receptivity to injection operations.

The use of existing site infrastructure—including wells, pipelines, meters, fluid separation systems, dehydrators, compressors, and pumps—saved project time and resources. A review of existing wells' conditions in the main test field determined that the most cost-effective strategy was to rework three open wells for use in injection and monitoring. The three wells involved already had EPA Class II UIC Permits. These wells were equipped with standard oilfield wellheads for CO_2 injection and dial gauges for measuring pressure and temperature at the wellhead. The piping was equipped with tee-fittings to allow for additional gauges. Workovers were performed to update the existing injection well to meet MRCSP project needs, and to reconfigure two production wells into monitoring wells.

Pre-existing central processing and compression facilities used for CO_2-EOR were used for MRCSP large-scale injection operations (see figure below). The compression and dehydration facility was used to process amine-separated, high-purity CO_2 (98 percent purity) derived from natural gas processing for transport to the central processing facility. At the central processing facility, CO_2 produced with the oil recovered from other fields within the project boundary was recycled, integrated with the high-purity CO_2, and distributed to injection wells. Daily production and injection data was used for computing relevant CO_2 metrics.

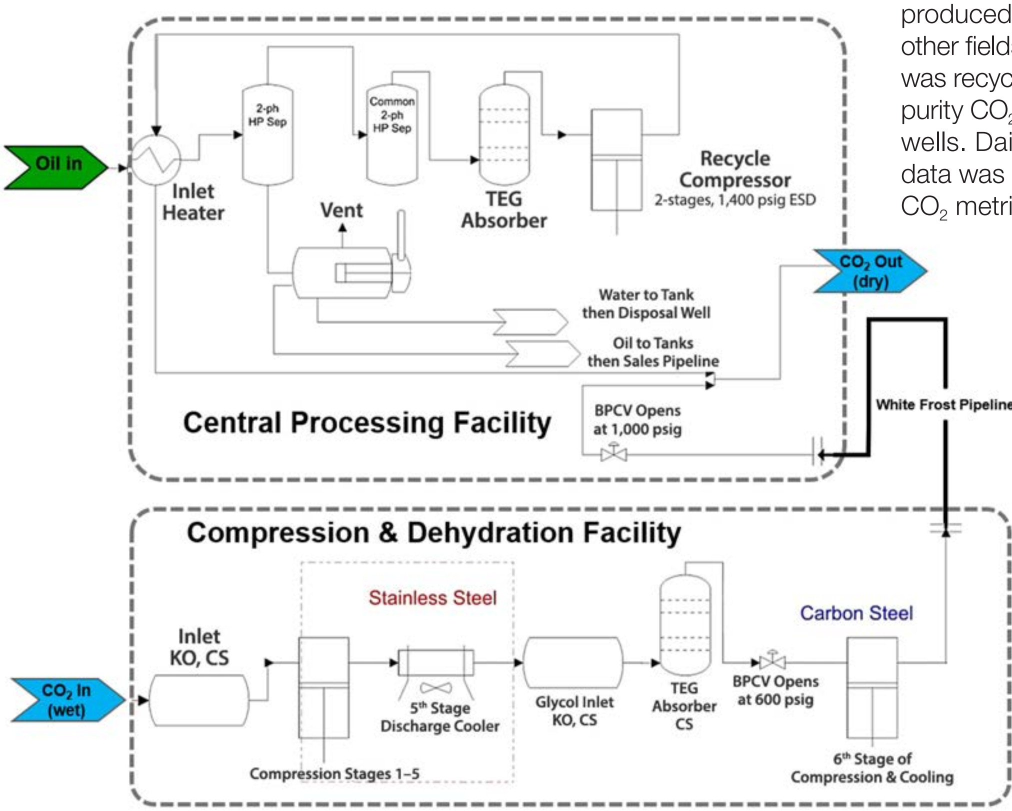


Diagram showing existing processing and compression facilities that the MRCSP Development Phase project uses for large-scale CO_2 injection.

CASE STUDY 4.12 — **SWP**

SOUTHWEST REGIONAL PARTNERSHIP ON CARBON SEQUESTRATION (SWP)

Forming Good Relationships with Partners, Landowners, and Other Stakeholders Through Social Characterization

In the case of CO_2 storage associated with projects in areas where oil and gas production has historically occurred, it can be beneficial to work with contacts in the local industry. In both Validation Phase and Development Phase projects, the Southwest Regional Partnership on Carbon Sequestration (SWP) relied on industry partners to help with characterization and identification of key people, organizations, and potential issues facing each field project.

The Farnsworth Field, Texas (Farnsworth Unit Project) is a region with a long history of exploration and production, so most of the population is familiar with oil and gas-related activities. Initial social characterization included a survey of newspapers and community websites located in the area. Characterization also relied heavily upon the knowledge of field personnel and landmen employed by Chaparral Energy, SWP's industry partner in the project.

While landowners in the area were receptive to oil and gas activities at a normal level and had little problem with the idea of CO_2 injection for storage or EOR, SWP learned that extensive surface seismic work, the use of tracers, water well sampling, and increased workovers of project-related wells had the potential to cause friction with landowners in this highly agricultural surface landscape. Chaparral Energy formed good working relationships with landowners and area stakeholders, and the partnership added to those efforts by holding town meetings and face-to-face communications with affected surface owners. Initial introductions were made through Chaparral's personnel who were familiar with the area, the stakeholders, and the issues.

Issues with potential for causing friction included disruption of agricultural activities, disturbance of land or crops during growing seasons, and unusual traffic from various monitoring teams. As part of the effort to maintain good relationships, SWP worked with landowners regarding scheduling of data collection and monitoring activities. All owners who gave access to their groundwater wells were provided with results of sample analyses annually. Efforts were made to place data collection sites either on existing well pads or along the edges of local and county roads where they had the least impact on farming. Any kind of activity that might impact crop growth was scheduled when there are no crops on the ground and no active irrigation. Monitoring teams always checked with the Chaparral's field office and local landowners who may be in the area before accessing any of the water wells.

Successful projects cultivate good working relationships with landowners. At Farnsworth, characterization work with the greatest land impact, such as drilling or seismic surveys, are generally timed for winter, when the ground is frozen. In the summer, the farmland is irrigated and all equipment is designed to minimize interference with agricultural activities. Wellheads, equipment sheds, and other surface facilities are planned, where possible, to be short enough to fit under the arms of center pivot irrigation systems. Fixed stations for soil flux measurements are placed at the edges of fields along rights-of-way so they will not be damaged by plows and other agricultural equipment.

5.0 SITE CHARACTERIZATION

Site Selection concludes, in successful cases, with one or more Potential Sites being elevated to the Site Characterization stage. The purpose of Site Characterization is to systematically scrutinize a Potential Site to define its storage-related attributes and determine whether it should be ranked as a Qualified Site. Once a site has achieved rank as a Qualified Site, its storage resources are classified as Contingent Storage Resources, and it is considered ready for development.

As with Site Selection, Site Characterization requires assembling a multidisciplinary team to plan all technical and nontechnical components to be analyzed during the Site Characterization process. The process is generally divided into two stages: Initial Characterization and Detailed Characterization. Activities and analyses that use existing data and information are considered part of Initial Characterization, while activities that require acquisition of new and additional data are considered part of Detailed Characterization.

Table 5.1 and Figure 5.1 illustrate the components for evaluation that are the focus of the Initial Characterization process. Table 5.2 and Figure 5.2 illustrate the main components that are evaluated during Detailed Characterization. These components are described in detail in Section 5.1 (Initial Characterization) and Section 5.2 (Detailed Characterization).

Table 5.1: Guidelines for Initial Characterization

PUBLIC OUTREACH NEEDS	Assess Outreach Needs	Goals and Activities	Create a timeline of goals and activities to define likely outreach needs for Potential Sites.
		Outreach Team	Establish outreach team with range of expertise needed to address public concerns in an effective way.
		Stakeholders and Social Climate	Identify stakeholders, evaluate social climate, and assess likely concerns and perceptions related to the project.
		Public Outreach Program	Develop an effective public outreach program to address anticipated outreach needs.
REGULATORY REQUIREMENTS	Analyze Regulatory Issues	Applicable Regulations	For each Potential Sites, determine applicable Federal, state, and regional regulatory requirements for site characterization and site development activities.
		Well Plan(s)	Develop well plans for anticipated appraisal wells, injection wells, and monitoring wells.
		UIC Permit Planning	Prepare for UIC permit application(s) by consulting with regulators and obtaining feedback on initial well plans and site development plans.
RESERVOIR FRAMEWORK DATA	Characterize Subsurface Geology	Geological and Geophysical	Establish geologic and geophysical framework of targeted injection and confining intervals for each Potential Site.
		Geochemical	Establish baseline geochemical data on fluids in the injection zone and in shallow groundwater aquifers above the injection zone.
		Geomechanical	Establish baseline geomechanical characteristics of targeted injection and confining zones.
		Hydrogeological	Establish hydrogeological characteristics of injection and confining zones to assure reliable containment of injected CO_2.
MODEL DATA	Build and Calibrate Models	Build and Calibrate Models	For each Potential Site, build static and dynamic model frameworks and populate with site-specific data for target reservoir.
		Test Models	Test scenarios for a range of reservoir parameters and boundary conditions.
		Compare Outputs	Compare model outputs to ensure consistency and reliability of models.
SITE DEVELOPMENT	Create Initial Site Development Plan	Detailed Characterization Phase	Develop data acquisition and analysis plan for Detailed Characterization phase.
		Development Phase	Update Site Development Plan to include Detailed Characterization and Site Development.

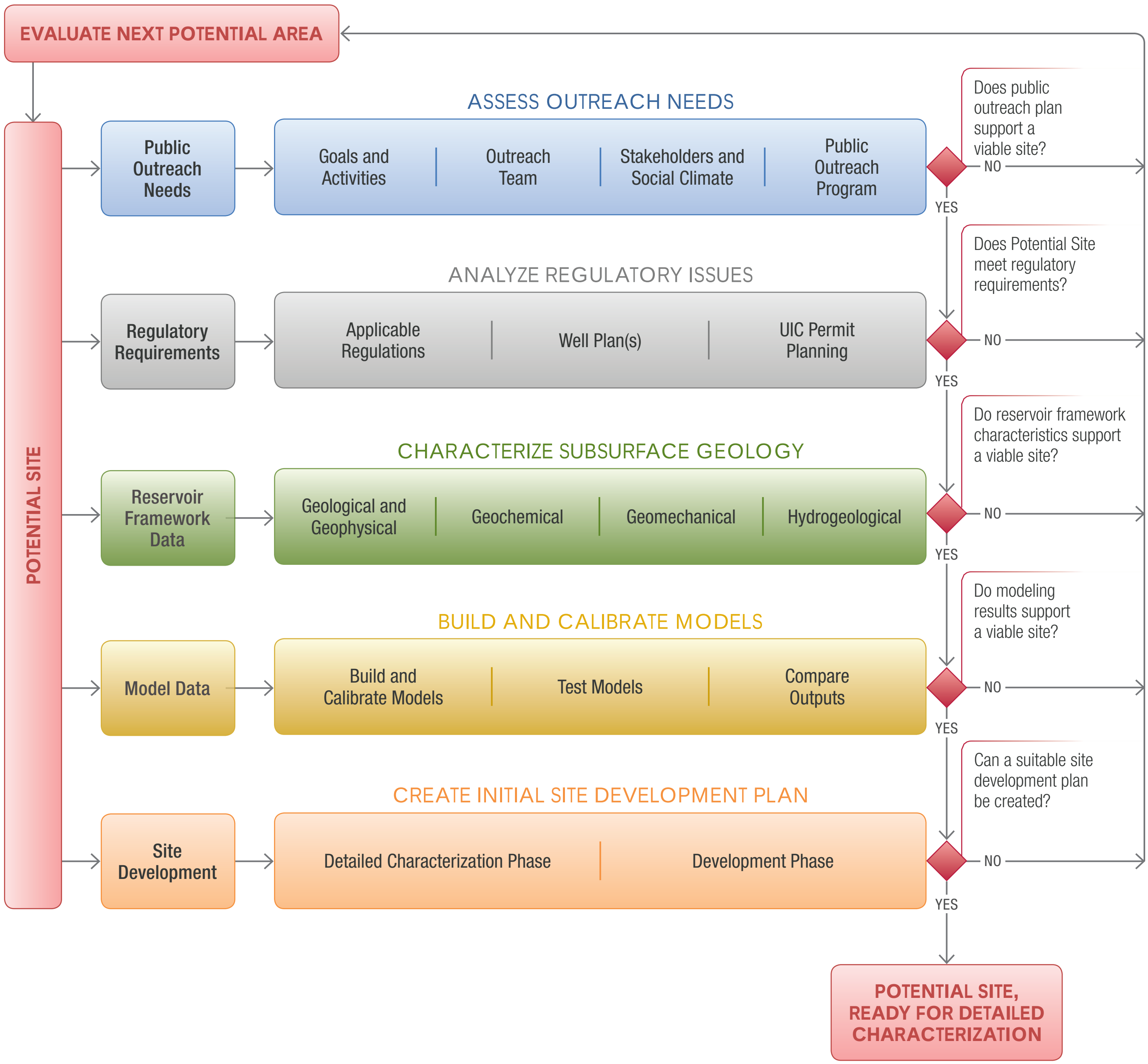


Figure 5.1 Flowchart for Initial Characterization

5.1 INITIAL CHARACTERIZATION

As shown in Table 5.1 and Figure 5.1, Initial Characterization of Potential Sites is carried out using existing data and encompasses evaluation of five primary components: (i) Public Outreach Needs, (ii) Regulatory Requirements, (iii) Reservoir Framework Data, (iv) Model Data, and (v) Site Development Needs. Initial Characterization analyses are designed to answer the questions posed at each component decision gate, as indicated by the red diamonds in Figure 5.1. At each decision gate, a "no" response shifts the analysis back to the beginning of the process, while a "yes" response leads to the decision to proceed to the Detailed Characterization Phase (Section 5.2).

The first step is to evaluate the site-specific Public Outreach needs of the Potential Site so that a successful outreach plan can be developed and implemented.

5.1.1 PUBLIC OUTREACH PLAN FOR POTENTIAL SITE

The Public Outreach needs of the Potential Site must be analyzed, so that a detailed, site-specific Public Outreach Plan can be developed. Note that this analysis is intended to follow up on preliminary public outreach studies initiated during Site Screening and Site Selection (see Chapters 3 and 4). In addition, all Public Outreach analysis and planning will follow the guidelines in DOE's BPM on "Public Outreach and Education in Geologic Storage" (NETL, 2016f).

The project's Public Outreach assessment will include: (1) creating a timeline of project goals and activities to define likely outreach needs; (2) establishing an Outreach Team with the range of expertise needed to address public concerns; (3) identifying stakeholders and characterizing the social climate to assess potential concerns and perceptions related to the project; and (4) developing and implementing a Public Outreach Plan with specific steps for interacting with stakeholders. Progress in outreach activities will be continually evaluated, and the Public Outreach Plan will be revised as needed to improve its effectiveness.

It is important during Initial Characterization to develop a realistic sense of the level of effort needed to fully implement the Public Outreach Plan. After the timeline of project goals and activities is developed, anticipated public interaction associated with these activities can be mapped into the timeline, and the Outreach Team can be adjusted to include all the necessary skillsets. The Outreach Team will identify stakeholders and evaluate the social climate to anticipate concerns and develop effective communication pathways for interacting with stakeholders.

5.1.2 REGULATORY REQUIREMENTS FOR PROPOSED SITE

During the Site Selection stage, the project developer reviewed regulatory requirements affecting Selected Areas (see Chapter 4). During the Initial Characterization stage, the project developer must analyze the Regulatory Requirement component in greater detail, with specific focus on regulations for geologic storage development of the Potential Site under scrutiny.

Although there are many regulatory issues, this section focuses on UIC well planning and permitting preparation. It is extremely important to understand the data requirements for UIC regulations to make certain the project is acquiring the data necessary to meet those regulations. There are three elements in this analysis: (i) Determining Applicable Regulations, (ii) Developing Well Plans, and (iii) Preparing for UIC Permit Application(s).

Case Study 5.1, from BSCSP, describes strategies for incorporating regulatory requirements early in Initial Characterization, so that appropriate time and resources are dedicated to meeting data requirements and obtaining all necessary information for UIC permit applications.

▶ See page 85

DETERMINE APPLICABLE REGULATIONS

The project developer must obtain all Federal, state, and regional regulatory requirements for anticipated Site Characterization and site development activities, which may include acquiring seismic data or other geophysical survey data, drilling a stratigraphic test well, and drilling an injection well and monitoring wells. The regulatory assessment carried out during Site Selection should be revisited to check that all local agencies and jurisdictions have been identified. Timelines, and data needs for completing the permitting processes should be re-assessed and Project Definition timelines and resource plans updated as necessary. The developer must also review additional requirements for carbon storage (e.g., pipeline development, land access, and pore rights). This information will be used to assess the feasibility of the Potential Site.

Site-specific data requirements for Class VI wells should be reviewed. As discussed in Section 4.2, UIC regulations require extensive data on target formation porosity; information on the seismic history of the site and in situ fluid pressures; maps and cross-sections of USDWs near the injection zone; information on faults or fractures transecting confining zones; and geochemical data on fluids in the injection zone, confining zones, overburden layers, and USDWs. These requirements can be fulfilled by implementing a variety of Site Characterization tools.

UIC Class VI rules also require the use of sophisticated computational models to define the AoR and evaluate the extent of injectate plume migration and pressure propagation. The models incorporate specific conditions at the site, as well as the scope of the injection project, based on volume, rate, formation depth, pressures, and duration of injection. Computational models for Class VI wells should be based on the analysis of Site Characterization data collected from the injection and confining zones, taking into account any geologic heterogeneities and potential migration pathways through faults, fractures, and artificial penetrations such as unplugged or abandoned wells.

Case Study 5.2, from the SECARB Cranfield Project, illustrates the importance of understanding groundwater attributes and applicable regulations for the site's groundwater system-- which is protected from damage by the EPA and may require monitoring.

▶ See page 86

DEVELOP WELL PLANS

During Initial Characterization, the project developer must determine the types of wells to be drilled at the Potential Site. Well planning must be carried out for: (1) appraisal wells, to be drilled and logged to support Detailed Characterization; (2) injection wells to be drilled if and when the project is elevated to the Site Development Stage; and (3) monitoring wells to be drilled to monitor underground containment of CO_2 in the storage reservoir.

Each anticipated well will require a well plan, with details of well design, construction, testing, injection, and monitoring. It is essential that all well plans be in compliance with Federal, state, and regional regulations for the wells being planned. Planning should consider whether the wells will be vertical or horizontal and address specific planning issues accordingly. The well plan shall address four primary activities: (i) Well Design, (ii) Formation Evaluation, (iii) Well Testing, and (iv) Injection Tests.

Well Design

Well design is dictated by the ultimate use of the well. If the well is to be used as a stratigraphic test or appraisal well, the well design will focus primarily on formation evaluation. If, however, the well is to be considered as a future injection well, a UIC Class VI permit must be obtained. In all cases, well design must be approved by the appropriate regulatory agency. EPA has published a guidance document (EPA, 2012) that provides construction and testing requirements for Class VI wells. Additional discussion of well construction and testing for geologic storage is found in DOE's "Best Practices for Operating Carbon Dioxide Storage Projects in Deep Geologic Formations" (NETL, 2016a).

Formation Evaluation

The well plan should address data gathering activities or tests to be performed in a new wellbore to characterize the injection and confining zones. These activities should be tailored to the specific site based on the level of certainty already achieved during the Initial Characterization. Activities at this stage may include: sampling whole cores of potential injection and confining units; obtaining standard and advanced logging suites; obtaining sidewall cores to complement whole cores taken; performing geologic and hydrologic characterizations of above-zone monitoring intervals; and collecting fluid samples for geochemistry analysis. Analysis of cores, formation fluids, pressure readings, and logs should be directed toward better delineation of both the injection and confining intervals at the site.

Well Testing

The well plan should include well tests, such as a drill stem test (DST), which the project developer may want to conduct to further determine reservoir properties and permeability before proceeding to well completion. DSTs are commonly used in the oil and natural gas industry to acquire additional information about fluids, pressures, areal extent of the reservoir, and pressure boundaries.

Injection Tests

The well plan should also describe injection tests (brine or CO_2), which may be undertaken to validate the existence of sufficient permeability and identify potential permeability barriers for required injection rates and pressures in a potential reservoir. This might include a series of step-rate injection tests to confirm that the reservoir can support the planned injection regime. Refer to the EPA step-rate testing procedure for additional details on conducting a step-rate well test. Another type of test to be considered is a small-scale, hydraulic fracture stress measurement to determine in situ stress magnitudes and directions. Any type of injection test should be compliant with the well design and permitting requirements. The team should make certain to coordinate with the appropriate permitting agency prior to drilling the well, to ensure that the tests can be completed with the permit granted.

PREPARE FOR UIC PERMIT APPLICATION

Continuing consultation with regulators, begun during Site Selection, can help the project developer avoid unanticipated permit costs and project delays. Project developers should obtain feedback on initial well plans and site development plans to confirm that assessments align with UIC and other regulations.

In addition, developers should revisit existing and abandoned wellbore integrity data collected during Site Selection, focusing on the subset of data specific to the Potential Site. Additional analyses may be warranted. For example, if a well is producing within the AoR boundary, confirmation should be secured to indicate that tubing and casing pressures are continually monitored and recorded and not operated outside of the permitted ranges. Wells that may be of concern as potential leakage pathways (older wells, noticeable structural damage, etc.) can be pressure tested for mechanical integrity. If the pressure test fails, both cement bond and casing caliper logs can be used to determine the overall integrity of the casing and cement and provide insights regarding possible remedial actions. The list of existing wellbores within the AoR may need to be updated if the AoR boundary changes as a result of modeling performed during Initial Characterization.

5.1.3 RESERVOIR FRAMEWORK DATA

Building on previous analyses conducted during the Site Selection stage, data analysis at this stage gains greater focus as site-specific elements of the Reservoir Framework Data component are assessed. These elements include: (i) Geological, (ii) Geochemical, (iii) Geomechanical, (iv) and Hydrogeological data analyses to improve the project developer's knowledge of specific attributes of the injection reservoir and confining intervals at the site. These analyses are based on existing datasets, which might include outcrop data, seismic survey data and interpretations, offset well logs, offset well cores, and offset production-testing results.

The project developer is strongly encouraged to create an online characterization database to facilitate seamless data and information sharing among project partners. The volume and complexity of data that are gathered and utilized during Site Characterization can be overwhelming. Data and information brought to the project are likely to include seismic reflection data, well log data, field and outcrop data, models and simulations, geographic information system (GIS) data, technical publications, internal reports, and illustrations. It is a challenge to ensure that all individuals have access to correct files, and that all project partners are kept abreast of data and information updates. This is especially challenging in a project that taps into the expertise of many individuals, from multiple institutions, located in widely separated regions.

An online database or active archive can be established with all datasets in most up-to-date versions and with communication software that provides data sharing, data transfer, and opportunities for discussions among project team members on an ongoing basis.

In Case Study 5.3, the Southwest Regional Partnership on Carbon Sequestration (SWP) recommends the use of Velo, which can handle large volumes of data and interpretations. It was developed by the Pacific Northwest National Laboratory (PNNL) for scientific and technical collaboration in a secure environment.

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GEOLOGICAL AND GEOPHYSICAL DATA EVALUATION

During Initial Characterization, the project developer must establish details of the geologic framework of the candidate injection interval at the Potential Site being analyzed. This evaluation will most likely be based on existing well and seismic data. The first step is to evaluate existing data that may be available from vendors or operators. Existing 2D or 3D seismic data, for example, may be available for purchase or for reprocessing. Similarly, existing well logs that are not in the public domain may be available for purchase. Existing data must be purchased and potential costs assessed. However, the costs are likely to be significantly less than costs to conduct a new seismic acquisition survey or drill a new appraisal well.

Case Study 5.4, from the SECARB Citronelle Project, provides an example of innovative use of existing vintage geophysical well logs for formation evaluation and estimating porosity and permeability in the Paluxy Reservoir.

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Case Study 5.5, from the MGSC Illinois Basin-Decatur Project, discusses the use of borehole seismic data for identifying key stratigraphic intervals in the Mt. Simon reservoir.

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Case Study 5.6 provides a discussion of SWP's Pump Canyon project, in the San Juan Basin, and Farnsworth Unit Project, in the Anadarko Basin. Both are examples of projects where legacy 2D seismic lines were made available for purchase at a small fraction of the cost to acquire new seismic data. In both cases, the purchased 2D lines made reliable interpretation of subsurface reservoir geology and reservoir structure possible.

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Framework geology data and information for the Potential Site should ideally include a site-specific type log/stratigraphic column including: a detailed correlation diagram of the subsurface architecture at the site that identifies and illustrates the targeted injection interval(s) within the injection zone and confining interval(s) within the confining zone; structural maps of the injection and confining zone(s); a depositional model of the reservoir and seal; facies distribution maps of the reservoir and seal; and porosity maps for injection and confining intervals and injection and confining zone(s). Site-specific information on reservoir petrology, including mineralogy, porosity, and pore throat geometry, may also be important, as these properties may influence rock/CO_2 interactions during injection.

Case Study 5.7, from the MGSC Illinois Basin-Decatur Project, emphasizes the need for detailed studies of the mineralogy and petrology of both reservoir and seal to determine physical, geochemical, and mineralogical changes that may occur during and after injection.

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It is important at this stage to gather all existing geologic information that may be required for an injection permit, so that the project developer is prepared in advance for the permitting process. This geological data evaluation will be updated and improved during Detailed Characterization, as additional data are acquired.

Case Study 5.8, from the SECARB Cranfield Project, discusses the importance of including geologic overburden units, which lie above the injection zone, in the reservoir framework analysis conducted during Initial Characterization.

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GEOCHEMICAL DATA EVALUATION

Geochemical data evaluation during Initial Characterization is intended to establish the baseline geochemistry of fluids in the injection zone and in shallow groundwater aquifers above it. Information and data from the injection zone can be obtained from offset wells, if available. Fluid property data, including composition, pH, and conductivity, can be combined with data on reservoir and caprock mineralogy to model brine-CO_2-formation reactions that may occur within the injection zone and at the confining zone interface. Such modeling is valuable, because chemical reactions induced by CO_2 injection may cause changes in reservoir porosity and permeability over time. In addition, permitting requirements may require annual sampling and analysis of formation fluids. Baselines established during Initial Characterization may fulfill this requirement.

Geochemistry data should also be obtained from all shallow aquifers at the site that are known or suspected to contain USDWs. The project developer may be able to obtain these fluid samples using existing water wells near the Potential Site. Geochemical analysis of water samples will be used to establish groundwater quality for future monitoring. Baseline groundwater samples are typically part of the MVA plan and should be collected prior to first injection of CO_2. Future sampling and analytical results will be compared against this baseline.

The majority of industry well files do not contain geochemistry data from shallow aquifers. They only contain data from the formation that was being tested for hydrocarbons. Also, the collection of truly representative fluid samples from previously un-sampled formations within existing wells is logistically and technically challenging and, in many cases, impossible. Developing baseline geochemical data on all aquifers in a study area is likely to be difficult, and the developer should focus efforts on those known to contain USDWs.

GEOMECHANICAL DATA EVALUATION

Modeling the mechanical effects of CO_2 injection and storage in the injection zone is essential for understanding the integrity of the confining zone and assessing the risk of induced seismicity. To address these issues, the project developer should run a series of injection simulations to assess the integrity of the confining zone under various injection schedules, rates, and pressures. Simulation results will allow the project team to forecast the pressure propagation distribution for anticipated CO_2 injection over an extended time period. The resulting stresses in the subsurface are a result of pore pressure increases related to injection rate, injection volume, buoyancy forces, and displaced brine. Proper geomechanical characterization and management of pressure can reduce the risk of induced seismicity.

For an injection permit, current regulations typically require that maximum allowable surface injection pressure be established prior to injection. Currently, the maximum allowable injection pressure cannot exceed a designated percentage of the fracture pressure of the injection formation, which is often expressed as a fracture gradient. If faults are present within the pressure-affected regime, the stipulated injection schedule and maximum injection pressure might also be affected by the potential for induced seismicity. A dynamic 3D geologic model should be developed that includes fault locations, orientations, and dimensions, as well as the regional stress orientation and magnitude, if known. Site-specific simulations may also include estimates of in situ stress, pore fluid pressures, hydrologic boundary conditions, and historical seismicity.

Geomechanical baselines can be established by analyzing advanced logging suites. Cores and logs, including those from offset wells that penetrate through injection and confining zone(s), should be examined for evidence of faulting and fracturing. Site-specific stress data from borehole breakouts can be used to determine in situ stress magnitudes and orientations in offset wells. Geomechanical parameters should be updated whenever new data become available to improve the accuracy and reliability of models and simulations.

Collection of data on faulting, along with geomechanical modeling, is consistent with recommendations made by the National Research Council (NRC, 2012) for addressing the potential for induced seismicity associated with storage projects. The NRC recommends that information on fault location, seismic activity history, and in situ stress state be collected as a first step in determining if injection is likely to cause seismicity intense enough to pose a potential hazard. The NRC also recommends further research to develop linked geomechanical/seismic activity simulation models that can be used to help identify the most critical geological characteristics, fluid injection parameters, and rock and fault properties controlling induced seismicity.

The project developer should be able to use geomechanical baseline data, developed during Initial Characterization, to prepare for future permitting requirements.

HYDROGEOLOGICAL DATA EVALUATION

A thorough understanding of the hydrogeological environment within the injection zone is necessary for Initial Characterization of a Potential Site. Hydrogeological analysis relies on three types of reservoir data: (1) location(s) of water and other fluids, (2) properties of water and other fluids (especially chemical properties), and (3) existing or potential flow patterns of water and other liquids.

Prior to injection of CO_2, project developers must assess the hydrologic performance of the injection and confining zones through a series of tests designed to observe pressure responses to injected or extracted fluids. These tests provide assurance that the selected injection zone can accept the planned fluid volumes without exceeding pressure limits, and the confining zone(s) are effectively limiting vertical flow at acceptable levels.

> *Case Study 5.9, from the MRCSP project in Eastern Ohio, illustrates an example of utilizing flow-meter logging data and pressure fall-off data from brine disposal wells to identify viable CO_2 storage reservoirs in the study area.*
>
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A variety of hydrogeological tests may be conducted. Initial tests can be conducted by extracting small volumes of fluid under open-hole conditions. These can be useful for determining where to set perforations for larger-scale tests. Larger-scale hydrologic tests increase confidence in the injection zone response and should be conducted over a period of hours to days to demonstrate reservoir continuity.

Single-well tests may be conducted by pumping fluids from a well, or injecting fluids into a well, while observing the pressure response in the same well. Such tests provide direct evidence of injectivity and are referred to as pressure build-up and pressure fall-off testing. These tests can be conducted with any fluid. However, use of native formation brine can be affordable and appropriate, when CO_2 is not available.

Multi-well tests, where injection or extraction occurs in one well while the pressure response is observed in nearby wells, can be used to increase confidence in suitability of the injection zone to handle the planned injection rates over a sustained time period. The performance of the confining zone can be tested through measurement of stable pressure above the confining zone(s), as fluids are injected into or extracted from the injection zone. This type of test requires access for a pressure measurement in a permeable zone above the confining zone. This can be accomplished through various approaches, including pressure gauges on the outside of casing, multiple perforated intervals separated by packers, or a dedicated well perforated in an above-zone monitoring interval.

5.1.4 MODEL DATA

SELECT AND BUILD MODELS

During Initial Characterization, the project developer will gather all pertinent reservoir framework data for the specific site being evaluated, to build and test models for characterizing and predicting reservoir behavior at the Potential Site(s). Typically, a combination of models is used because no single model is capable of simulating all coupled reservoir processes at once. Model selection should include, at a minimum, a static earth model and a dynamic reservoir flow model.

A static 3D earth model is a valuable tool for integrating geologic, geophysical, geochemical, geomechanical, and hydrogeological properties of the injection zone within the context of the sedimentary basin at the site. The primary purpose of the static earth model is to provide a volumetric representation of the geologic framework of the injection zone. It also serves as the basis for dynamic reservoir simulations. The static geologic model may be built within the reservoir simulator by entering layer thicknesses, rock properties, and pore fluid properties, as well as geomechanical and geochemical properties.

> *Case Study 5.10, from the MRCSP Niagaran reefs, describes the use of wireline, core, and seismic data, along with other information, to develop a reliable static earth model of key horizons in the study area.*
>
> See page 95

Dynamic reservoir simulators are used to test various CO_2 injection scenarios and to characterize the short- and long-term storage performance of the reservoir. Storage performance may be assessed in terms of injectivity, capacity, containment, and even a quantitative or qualitative estimate of potential leakage. Dynamic reservoir simulators are generally based on numerical fluid flow models, and they need to be continually updated with new reservoir and fluid property data as they become available.

Reservoir modeling can also be used to optimize the design of the injection plan and forecast risks that may be encountered during the project, including unanticipated reservoir failure, leakage through faults or abandoned wells, and potential contamination of other resources, such as USDWs. Specific modeling applications for CO_2 geologic storage projects include, but are not limited to (Gupta et al., 2008):

- Evaluation of subsurface processes, including CO_2 phase behavior, advective forces, solubility, temperature and pressure effects, chemical reactions, and geomechanical effects
- Injection system design, well design, and pressure profiles
- AoR estimation
- Optimization of spatial and temporal monitoring strategies
- Risk assessment and MVA plan design
- Prediction of post-closure CO_2 plume behavior
- Site-closure decisions

To accurately and reliably apply models, multiple physical and chemical considerations must be included in the model's development. Detailed data related to these phenomena can be acquired from Initial and Detailed Characterization activities. Reactive transport modeling integrates all of the thermal, hydrogeological, and geochemical processes that are associated with dynamic geologic systems.

The project developer can account for flow, chemical reactions, and geomechanical properties by combining multiple models. Proper simulation of CO_2 geologic storage requires incorporating interdependent processes that must be modeled simultaneously to simulate the behavior of the injection formation. These processes include chemical reactions, molecular transport and diffusion, fluid flow, heat transfer, and mechanical stress and strain. A comprehensive discussion of modeling strategies for Potential geologic storage sites is provided in DOE's BPM "Risk Management and Simulation for Geologic Storage of CO_2" (NETL, 2016b).

TEST MODELS

As indicated earlier in this manual, the modeling process is iterative. During Initial Characterization, model frameworks are built and populated with geologic framework data. The models should be designed for optimization. Numerous model runs may be conducted, with varying parameters, and then tested for model functionality. Models should be properly calibrated (e.g., using well control). Sensitivity analyses should be used to assess uncertainties and evaluate the impacts of different parameters on the model outcome. The developer should fully document all input parameters, associated uncertainties, and model results, communicating the implications of the modeling results to the project team for feedback.

COMPARE OUTPUTS

Project developers should continue to integrate new data and analyses into the static and dynamic models. This involves developing and running various modeling scenarios for a range of parameters to test the injection design, optimize plume migration, and verify the expected definition of AoR, subsurface processes, and prospective storage estimates.

For example, data from subsurface analyses could be integrated into a numerical model of geochemical processes to investigate long-term consequences of CO_2 injection due to slow reactions between dissolved CO_2 and the host rock. A numerical model that can successfully predict the fate of CO_2 and its transport over extended periods must be able to couple hydrogeological, geomechanical, and geochemical reactions. Uncoupled fluid flow simulation and batch geochemical modeling are not sufficient to account for all the complexities and interactions expected to occur from geologic storage of CO_2.

The results of previous model runs should be compared with newly modeled data to ensure consistency and model functionality. Anomalies should be investigated and, if necessary, the model should be refined.

5.1.5 UPDATING INITIAL SITE DEVELOPMENT PLAN

At the conclusion of the Initial Characterization process, the decision must be made whether the Potential Site should be moved forward to Detailed Characterization and, ultimately, to Site Development. The project team will only recommend a Potential Site that has achieved "yes" responses at all decision gates indicated on the right-hand side of Figure 5.1. Specifically, to be promoted to Detailed Characterization, a Potential Site must have:

- A public outreach plan that is considered effective
- Well plans that meet regulatory requirements
- Reservoir framework characteristics that support a viable site
- Model results that support a viable site
- A suitable site development plan

A site with all of these criteria may be recommended for Detailed Characterization, which is the last stage of the project before the site goes to development for geologic storage. The costs associated with Detailed Characterization are substantial. Therefore, only sites with favorable Initial Characterization results will be elevated to Detailed Characterization.

In preparation for Detailed Characterization, the project developer will evaluate what additional steps are needed to advance the site to future development. The results of this evaluation will be enumerated in a Detailed Characterization Plan that addresses how to fill data and information gaps in the areas of public outreach, geological and geophysical data acquisition, reservoir modeling, and site permitting.

The project developer will also update the Site Development Plan at this time, by building on the preliminary plan created during the Site Selection stage (see Chapter 4). The updated Site Development Plan should include: (1) an update of Prospective Storage Resource calculations based on all completed reservoir framework and modeling analyses; (2) an updated Risk Assessment that includes an evaluation of the reservoir and confining intervals to ensure that the project has capacity and containment that is adequate to accommodate the volume of CO_2 established in the Project Definition; (3) initial development scenarios for planned injection, including the number of injection wells and monitoring wells, amount of CO_2 to be injected, and supporting economic analyses; (4) other infrastructure needs, including roads, facilities, and pipelines; (5) MVA and project reporting plans; (5) operational issues and mitigation plans; and (6) the project's Public Outreach Plan, which addresses ongoing interaction with stakeholders during site development.

Table 5.2: Guidelines for Detailed Characterization

OUTREACH PLAN	Update and Engage in Continuous Outreach	Update Project Timeline, Public Concerns, Stakeholders	Revise project timeline for designated Potential Site, to include new data acquisition activities and impacts; identify public concerns related to new activities; identify additional stakeholders.
		Update and Engage Outreach Plan	Update Public Outreach Plan and initiate outreach efforts on an ongoing basis.
GEOLOGICAL AND GEOPHYSICAL DATA	Acquire and Analyze New Data	Outcrop Studies	Conduct detailed mapping, sampling, and analysis of storage reservoir and caprock intervals within the vicinity of the designated Potential Site.
		Geophysical Data Acquisition	Conduct 2D or 3D seismic or other geophysical survey for improved stratigraphic and structural characterization of reservoir and caprock intervals.
		Appraisal Well	Drill and log appraisal well, if needed, to constrain site-specific reservoir properties and caprock integrity.
		Pre-Injection CO_2 Baseline	Establish pre-injection CO_2 baseline levels to support future monitoring.
MODELS	Update and Refine Models	Data Integration	Integrate all newly acquired outcrop, seismic, and well data into static and dynamic models for the designated Potential Site.
		Model Refinements	Refine static geologic model and reservoir simulations.
PERMITTING	Assemble Complete Permitting Package	Qualify Site	Assemble data and information needed to illustrate that the designated Potential Site should be elevated in status to Qualified Site.
		Assemble Permit Data	Assemble all data, information, and documents required for permitting.

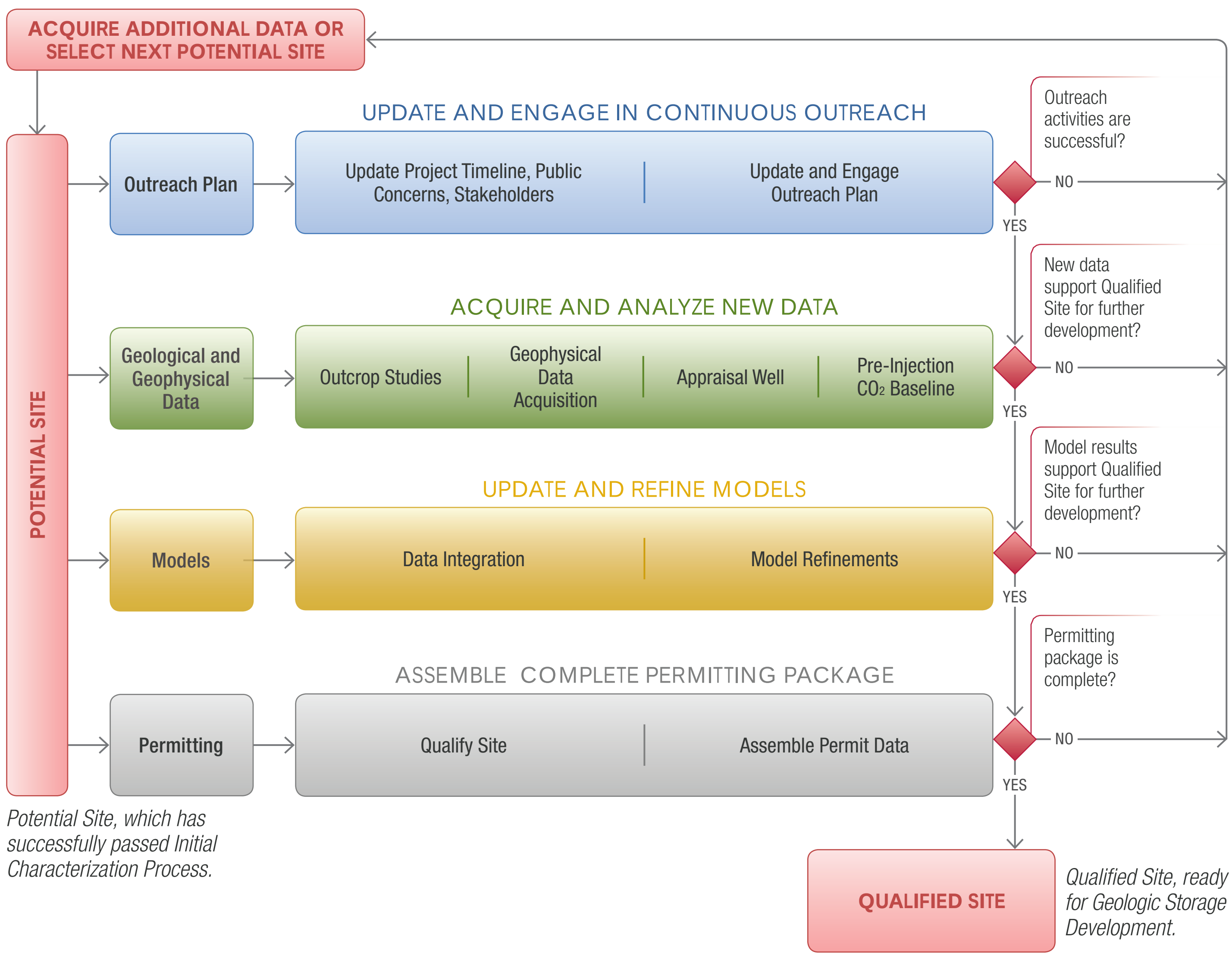

Figure 5.2 Flowchart for Detailed Characterization

5.2 DETAILED CHARACTERIZATION

Detailed Characterization is initiated when the above criteria are met, and the project developer has determined that additional data are needed to evaluate whether the designated Potential Site has all the components needed to become a Qualified Site. The project moves forward and new data are gathered to fill knowledge gaps and provide a more detailed picture of the storage reservoir and associated caprock that represent the CO_2 injection target. Detailed Characterization is carried out according to a Detailed Site Characterization Plan developed during the final stages of Initial Characterization. The Detailed Site Characterization Plan may include acquisition of new outcrop data, new seismic data, and drilling and testing an appraisal well if needed.

In some instances, the Potential Site being evaluated may reside in an oil or natural gas province where substantial outcrop, well log, and/or seismic data were collected previously and are readily available to the project team. In such cases, Initial Characterization process would have used the existing data and possibly determined that the target reservoir interval has suitable permeability, injection potential, and integrity to become a Qualified Site. However, in most cases, additional data are needed to complete the evaluation and validate the injection potential of the site.

Detailed Characterization builds on the previous studies conducted during Initial Characterization to develop a more detailed understanding of the Proposed Site and to obtain site-specific facts needed to promote it to a Qualified Site that is ready for development. Detailed characterization may include additional drilling and testing of wells to understand the geomechanical, geochemical, and hydrologic properties of the reservoir interval and its fluids. In addition, it may include acquisition and analysis of new seismic data for integration with new and existing well data.

Newly acquired data will be used to further understand the subsurface architecture of the storage reservoir and overlying and underlying units; define the areal extent of a project site; validate Contingent Storage Resource estimates for future financial investments; establish continuity of the injection and confining zones; and identify potential leakage issues that could be created by regional small-scale reservoir faulting or juxtaposition of injection or confining zones.

Carbon dioxide flux baselines may also be measured and established at this time to set the stage for future monitoring work. A detailed description of monitoring strategies and technologies is available in the BPM, titled "Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations" (NETL 2016g).

5.2.1 UPDATING AND ENGAGING PUBLIC OUTREACH PLAN

Prior to initiating Detailed Characterization activities in the field, the Public Outreach Plan developed during Initial Characterization will need to be revisited and updated to account for all new activities and their potential impacts. The Outreach Team will need to revisit the Project Goals and Activities, update information set forth in the existing Public Outreach Plan, and review staffing of the Outreach Team to be sure it remains in balance with planned activities.

Data acquisition activities may result in increased traffic at the site and in adjacent areas, a greater presence of project personnel and contractors onsite, and an uptick in water and electricity usage to support data gathering efforts. In addition, some data collection efforts may require installation of surface and subsurface instrumentation, equipment, facilities, and infrastructure.

People living and working near a Potential Site may have concerns related to increased traffic, increased noise levels, and other possible impacts from characterization activities and future injection operations. Some of these concerns may be discernible only by meeting in person with neighbors living in the vicinity of a Potential Site. For this reason, it is crucial that Outreach Team representatives meet with neighbors at this stage to identify and discuss their concerns and develop possible mitigation strategies.

The Outreach Team will need to: (1) revise the project timeline to include new data-gathering activities and impacts; (2) identify likely public concerns related to these planned activities; (3) identify additional stakeholders that may have an interest in subsequent stages of the project; and (4) update the Public Outreach Plan, accordingly. Updates to the Outreach Team and Public Outreach Plan, as well as implementation of outreach activities, will follow principles and guidelines set forth in "Best Practices for Public Outreach and Education for Geological Storage of Carbon Dioxide Projects" (NETL, 2016f).

Once the Outreach Team and Public Outreach Plan are updated, the revised plan should be fully engaged. Stakeholders should be notified, and the project team should communicate with local communities on process, timing, and potential impacts of upcoming data collection activities. Stakeholders may include Federal, local, and regional officials who can provide important information on property access. Outreach efforts will be conducted with stakeholders on an ongoing basis throughout the remaining life of the project.

Outreach efforts related to the site's potential development as a CO_2 storage facility are likely to be initiated at this stage. Steps should be taken to incorporate all anticipated future activities, including injection well permitting, surface installations, facilities construction, infrastructure construction, and injection operations into the Public Outreach Plan.

5.2.2 ACQUIRING, ANALYZING, AND INTEGRATING NEW SURFACE AND SUBSURFACE GEOLOGICAL AND GEOPHYSICAL DATA

This activity is focused primarily on acquisition and analysis of new geological and geophysical data needed to evaluate the suitability of the reservoir for long-term CO_2 storage.

CONDUCTING TARGETED OUTCROP STUDIES

In some cases, targeted outcrop studies may be a practical and cost-effective way to obtain detailed information about the properties of the storage reservoir and confining zone in the immediate area of the Potential Site being evaluated. Stratigraphic units representing the reservoir and seal may be exposed in surface outcrops along the margins of the site, and, in such cases, direct observation, measurement, and sampling of these units is possible.

Detailed mapping of reservoir facies and thicknesses in and adjacent to the site will indicate the degree of natural variability or heterogeneity within the storage reservoir and associated formations. In some cases, it may be possible to measure significant changes in unit thickness, as well as local variations in primary porosity and permeability within the local area of the Potential Site. In other cases, outcrop studies may show that the reservoir and seal maintain uniform thicknesses, porosity values, and other physical properties across large distances and throughout the site being characterized.

In either case, these observations are critically important for understanding the potential for complexity or heterogeneity of the reservoir and seal in the subsurface and being able to predict, with confidence, the physical properties of these units at the specific location where an injection well could be placed. Targeted outcrop observations and sampling may serve as valuable ground truth to substantiate interpretations of reservoir and seal properties in the subsurface as interpreted from seismic profiles or offset well projections and reduce geologic risks associated with the placement of a future injection well.

Outcrops may also provide firsthand observations of the structural complexity and integrity of the reservoir and seal. It may be readily apparent in surface outcrops that systematic fractures or other discontinuities are present in the targeted reservoir and impart a secondary porosity to the reservoir horizon. Measurement and analysis of geologic structures in the field, including detailed mapping of fracture orientation, fracture density, and fracture extent, can provide valuable knowledge that can be extrapolated into the subsurface and used to select the best portions of the reservoir for injection.

Careful outcrop studies may also make it possible to determine whether fractures or other structures penetrate the interface between reservoir and seal, thereby affecting the reservoir's structural integrity. These studies are critical for understanding possible compartmentalization of the reservoir, assessing the integrity of the seal, and detecting possible pathways for leakage.

ACQUIRING AND ANALYZING NEW GEOPHYSICAL DATA

Depending on the availability of existing data, it may be necessary, during the Detailed Characterization stage, to acquire new 2D or 3D seismic data. Borehole geophysical data, including VSP and crosswell data, may also be considered for acquisition. At this stage of the project, the Site Characterization Team must determine, with greater precision, the depth, thickness, and injection properties (porosity and permeability) of the reservoir interval. Without existing seismic data, this may be impossible, especially if well data are sparse. A carefully designed seismic survey can fill in the gaps and make it possible to map lateral changes in reservoir properties to provide reservoir information in regions that lie between existing wells.

Seismic data acquisition requires a significant financial investment, especially for 3D data acquisition, which is generally an order of magnitude more costly than 2D data acquisition. The advantage of acquiring new data, however, is that a new survey can be designed using survey parameters that will optimize data quality given the specific landscape, infrastructure, geologic framework, imaging depth of the site, and reservoir being imaged. Site-specific survey design can lead to more reliable rock property estimates for the targeted injection horizon; more reliable establishment of the seismic baseline for the site; and, consequently, a higher likelihood of successful time-lapse monitoring of CO_2 injection in the future. Specific guidelines for collecting seismic baseline data for future monitoring work can be found in DOE's BPM "Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations" (NETL, 2016g).

A 2D seismic survey that ties into existing well control can bring tremendous value to the Site Characterization effort. Two-dimensional data can be used to develop a detailed cross-section showing reservoir depth, thickness, and structure at the site. Such depth sections are utilized to inform static geologic models, simulation models, and, ultimately, they are likely to guide placement of injection well(s). Faults and other structural discontinuities may be apparent in 2D data, unless they are near-vertical and have little or no displacement.

Three-dimensional seismic data acquisition is expensive, but it opens a large realm of possibilities for data processing and analysis. Three-dimensional data are collected on a grid that results in a 3D volume. As with 2D data, a key to processing and interpretation of the 3D data volume is calibrating the seismic data to well logs in or adjacent to the survey area. After calibration, 3D depth volumes can be generated. In addition, seismic attribute analysis and seismic inversion techniques can be used to interpret rock properties of the reservoir and confining zone horizons throughout the data volume. Seismic inversion analysis may provide density, porosity, and lithology estimates that can be incorporated into static geologic models of the site. An examination of seismic attributes, such as velocity and acoustic impedance, may show a correlation with porosity. In such cases, it is possible to make a 3D model of the porosity of the reservoir interval.

Case Study 5.11, from the MGSC Illinois Basin-Decatur Project, is an example of utilizing seismic inversion technology to transform seismic reflection data into detailed rock property estimates for intervals within the Mount Simon Sandstone reservoir.

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At some Potential Sites, there may be an opportunity to conduct a 3D VSP survey using an existing borehole. A high-resolution VSP can provide excellent velocity control in the vicinity of the wellbore. Additionally, VSP data can provide highly detailed rock property estimates for reservoir and seal intervals near the well.

Electrical techniques, including Electrical Tomography, Controlled Source Electromagnetic, and Crosswell Electrical Resistance Tomography, are sensitive to pore fluids in the subsurface and can therefore be an important aid for estimating pore fluid saturation and pore fluid changes over time. Results of resistivity surveys can also establish baseline data for subsequent monitoring during CO_2 injection and post-closure phases to observe time-lapse changes in CO_2 saturation distribution.

Other geophysical approaches for Detailed Characterization of Potential Sites should also be considered at this stage. Aeromagnetic data, for example, can provide a useful indicator of geological structures in the subsurface including faults and fractures. Combined with seismic data, these independent geophysical techniques will typically reduce the ambiguity in seismic interpretations and help to locate, with greater certainty, important structural features.

DRILLING AND TESTING APPRAISAL WELL ACCORDING TO SPECIFIC NEEDS OF THE SITE

If the Potential Site under scrutiny does not have sufficient well control to map and characterize, with certainty, the reservoir and seal in the subsurface, it may be necessary to invest in drilling an appraisal well (also known as a characterization well). In some cases, fundamental geologic knowledge is still needed at this stage to improve reliability and reduce uncertainties in the site's geologic model. In other cases, historic well log data may be available, but modern measurements may be needed to calibrate historic data and constrain estimates of reservoir injectivity, storage capacity, and integrity of the caprock or geologic seal. In such cases, the project developer is faced with the need to drill and log a new appraisal well. Operational and technical aspects of drilling an appraisal well will follow the well plans developed during Initial Characterization. Specific site access issues and permit requirements also will have been established and obtained at that time. Additional guidelines associated with drilling operations at Storage Sites can be found in DOE's BPM "Operating Carbon Dioxide Storage Projects in Deep Geologic Formations" (NETL, 2016a).

In Case Study 5.12, from the PCOR Partnership's Fort Nelson project, an exploratory well was needed to better constrain the injectivity, storage capacity, and structural and stratigraphic integrity of the storage reservoir and confining zone. Well data were used to enhance the geologic model of the project area.

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At some Potential Sites, wellbores may be present that penetrate the injection and confining intervals. In such cases, it could be more cost-effective to re-enter an existing wellbore and conduct a formation evaluation, well testing, or injection test instead of drilling a new well. The project developer should consider all existing data, including the vintage of the well, and perform a cost and risk analysis to determine if utilization of the existing wellbore would provide the information needed to map and characterize the injection reservoir and caprock intervals. If the site cannot be qualified with existing well information or by re-entering an existing wellbore, then an appraisal well should be drilled. An ideal appraisal well for a storage project will focus on acquiring new log data; acquiring core and reservoir fluid samples; and conducting DSTs.

In Case Study 5.13, from the MGSC Illinois Basin Decatur Project, the decision was made to drill a well prior to investing in a 3D seismic dataset because there was, essentially, no well control at the site. Without well control, the existing 2D seismic data were difficult to interpret, and it was not possible to identify the storage reservoir with certainty in the 2D profile.

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In Case Study 5.14, from the SECARB Citronelle project, drilling new test wells was necessary for calibrating and interpreting reservoir property information that was obtained from vintage oilfield data.

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ESTABLISHING PRE-INJECTION CO_2 BASELINES

To comply with regulatory requirements and be prepared for CO_2 injection operations, the project team may take steps during Detailed Characterization to establish CO_2 flux baselines and other CO_2 monitoring-related baselines. Well-defined flux baselines are important for measuring CO_2 anomalies once a project moves to the development and injection stage. Knowledge of pre-injection CO_2 flux values can help reduce the risk that an unintended CO_2 release would go undetected.

Establishing flux baselines may include installation of aboveground sensors to measure the pre-injection flux of CO_2 to the atmosphere. The project team may also find it helpful to perform geochemical sampling of soil, vadose, and shallow groundwater zones for measuring near-surface CO_2 flux baselines. A wide variety of CO_2 flux monitoring tools may be employed to establish these baselines, depending on the specific needs of the site. Establishing a baseline for time-lapse monitoring of an injected CO_2 plume in the reservoir interval may also be considered at this stage. Four-dimensional or time-lapse seismic data can be used to image CO_2 plume migration in the subsurface, and this technique relies on having acquired a high-resolution, pre-injection image of the reservoir for comparison.

Many other types of CO_2 monitoring baselines are worthy of consideration at this stage of the project. For example, the project developer may wish to install surface displacement monitoring instruments to establish baseline elevations for monitoring future deformation and/or uplift of the ground surface due to CO_2 injection. Pre- and post-injection electrical resistivity surveys can even be utilized to estimate the CO_2 saturation distribution in the subsurface.

A detailed discussion of existing monitoring techniques is provided in the BPM, titled "Monitoring, Verification and Accounting of CO_2 Stored in Deep Geologic Formations" (NETL, 2016g).

Case Study 5.15, from the SECARB Cranfield project, provides an example of "one-time characterization" at several locations within a site providing an accurate and cost-effective baseline for future monitoring efforts.

See page 101

5.2.3 UPDATING GEOLOGIC MODEL AND REFINING RESERVOIR SIMULATIONS

During this stage, the static geologic model for the Potential Site, as well as reservoir simulations developed during Initial Characterization, will need to be updated with new outcrop, well, and geophysical survey data acquired during Detailed Characterization. Stratigraphic and structural data from outcrop studies may be projected into the static geologic model and incorporated into reservoir simulators. Similarly, all pertinent stratigraphic, structural, and rock property information from new 2D and 3D seismic interpretations will need to be incorporated. Newly acquired well log, core, fluid, and pump test data will also need to be incorporated into the models, so that the static model reflects the most up-to-date knowledge of the reservoir framework geology; and the reservoir simulator is properly constrained by all additional reservoir property, fluid property, and boundary condition information.

Case Study 5.16, from the MGSC Illinois Basin-Decatur Project, provides a brief discussion of using geophysical logs and cores to update information on sub-units within the Mt. Simon Sandstone.

See page 102

Case Study 5.17, from the PCOR Partnership, discusses the use of formation pressure testing to identify permeable horizons within the target injection zone for future monitoring.

See page 103

Case Study 5.18, from the SECARB Cranfield Project, illustrates an example of integrating wireline and whole core data into dynamic reservoir models, to improve their reliability.

See page 104

More specific procedures for updating Reservoir Simulation Models are provided in DOE's BPM "Risk Managements and Simulation for Geologic Storage of CO_2" (NETL, 2016b).

5.2.4 ASSEMBLING DATA NEEDED FOR PERMITTING AND QUALIFYING THE SITE

If all requirements of a viable CO_2 injection site are demonstrated, the Proposed Site is elevated in status to a Qualified Site, and the storage resource is classified as a Contingent Storage Resource. The project is ready at this stage to proceed to Site Development.

At this stage, the project developer assembles all data, information, and documents needed for permitting. This involves preparing all Site Characterization information, including the static geologic model and reservoir simulation model; compiling data and information on USDWs; updating all information on well conditions and well locations; assembling data on salinity and groundwater conditions; and having all data and information at the ready to submit the remaining permit applications for CO_2 injection operations.

A more detailed discussion of the permitting process is available in DOE's BPM "Operating Carbon Dioxide Storage Projects in Deep Geologic Formations" (NETL, 2016a).

5.3 RCSP CASE STUDIES

CASE STUDY 5.1 — BSCSP

BIG SKY CARBON SEQUESTRATION PARTNERSHIP (BSCSP)
Analyzing Regulatory Issues

A project's permitting and compliance strategy should identify regulatory requirements early and incorporate them into the design process for initial site characterization. Compliance with Federal and state regulations can have significant impacts on a project's scope and budget depending on the activities required to continue investment and prepare a UIC Class VI permit application. When conducting this analysis, projects must consider not only the Class VI requirements and natural resource-related regulatory requirements, but also regulations associated with waste management, worker safety and training, and long-term NEPA compliance. At the initial characterization stage, project personnel should include a permit and compliance specialist, or team of specialists, to fully evaluate site activities in a regulatory context.

The Big Sky Carbon Sequestration Partnership's (BSCSP) Kevin Dome project is located at an undeveloped greenfield site in north central Montana near the Canadian Border. The land ownership at Kevin Dome is a mix of Federal, state, and private, with split estate mineral and surface ownership. The area also includes protected environmental, biological, and cultural resources. During the site selection process, the team created a list of anticipated permits needed to conduct a large-scale injection project, as well as contacts for various agencies and general timelines to obtain major permits. As the project began the initial characterization stage, the team became aware of the high level of detail required to meet regulatory requirements and stay in compliance.

Despite initiating the characterization stage with a permitting plan, the team underestimated the amount of personnel time and budget that would be required for permitting. Landowner communications for both seismic surveys and well operations required numerous field visits, and cultural resources were more abundant than expected, requiring additional time and effort to identify, permit, and plan. The seismic survey was scheduled for late fall to adhere to requests from Federal agencies to limit effects on wildlife and reduce impacts to local farming activities. However, delays compounded as snow cover prevented the survey of cultural sites and icy conditions required extra safety precautions slowing progress of the seismic crews. Seasonal weather conditions also affected well operations. Cold weather complicated site operations and forced stand-by days, and wet conditions in spring had implications for storm water permitting and mobilization costs. Lastly, to ensure compliance with agency stipulations, work philosophies of service companies during all field components needed to shift from a time-driven paradigm to a compliance mode of operations. Several trainings were developed by the team to ensure all field personnel were trained on the regulations and values of the project.

As other projects transition from site selection to initial characterization, considerable effort should be focused on understanding the details and stipulations of required permits and how they affect project plans. This includes understanding the data requirements necessary to develop each permit as well as the time/cost of preparing and obtaining permit approvals. Consideration should also include anticipated project impacts relative to regulatory requirements for impact mitigation and long-term monitoring. It is also critical to understand potential site hazards, particularly safety risks to onsite personnel to comply with Occupational Safety and Health Administration (OSHA – worker safety) regulations. For example, if there is potential for sour gas exposure from downhole well activities, the project must incorporate safety controls into the well designs and operation plans to comply with natural resource and worker safety regulations. BSCSP found that hiring an in-house permit and compliance specialist with a foundation in natural resource regulatory compliance, health and safety, and field experience provided greater awareness and consideration of regulatory issues during decision-making. This expertise better informed best- and worst-case schedule and budget scenarios for project activities and allowed the team to prepare for unanticipated permitting complications.

CASE STUDY 5.2 — **SECARB**

SOUTHEAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (SECARB)

Considering Groundwater Attributes During Site Selection and Initial Characterization

During site selection and initial characterization, several attributes of the groundwater system must be considered. Because injection is deep and tentatively isolated from the groundwater system, initial work must be focused on the specific role(s) that groundwater may play in the project. During injection, groundwater is protected from damage by the EPA UIC Program, both for CO_2 injection into saline formations under the EPA Class VI Program and for sites engaged in injection of CO_2 for EOR under Class II. For this element, it is important to know how deep in the subsurface protected groundwater is found so that the cost of completing wells with required surface casing can be estimated. A second reason for characterization of groundwater is that it may be desirable or required under Class VI to monitor groundwater quality to document that it has not been impacted by injection. A third reason that groundwater may be assessed is to acquire and maintain public acceptance of injection in an area with a valued local groundwater resource. For the second and third elements, site selection and initial characterization needs are more extensive and include information on the number of aquifers, their utilization, past history, and hydrological and geochemical characteristics.

The Southeast Regional Carbon Sequestration Partnership (SECARB) Cranfield Project was conducted under Class II permits. As a result, groundwater monitoring was not required. However, the research team used the opportunity to mature technologies for future sites. The confined groundwater flow system at Cranfield extends to depths of 220 feet in the Miocene geologic section, and comprises three major hydrologically isolated flow systems. A minor perched aquifer is found in the alluvial and loess section at depths around 20 to 40 feet. Most of the groundwater supply wells in the local area use aquifers at depths of 200 to 400 feet, so these were the focus of the study. Fifteen wells drilled for water supply to support newly drilled injection wells provided good distribution of monitoring points over the study area.

Initial hydrogeology and groundwater chemistry data in the areas were rare, and regional study of groundwater was used to support initial assessments. The area is on a surface water drainage divide and potentiometric surfaces are relatively flat, but regional gradient is likely toward the western regional discharge points in the Mississippi valley and pumping center of the city of Natchez, Mississippi (Yang et al., 2013a). The dominantly clastic sediments in the aquifers contain few to no carbonates (Yang et al., 2013a; and Yang et al., 2013b). As groundwater wells were drilled, additional aquifer stratigraphy and mineralogy, groundwater flow, and groundwater chemistry characterization was undertaken (Yang et al., 2013a; and Yang et al., 2015a).

Several major innovations to the optimization of using groundwater for a storage site were contributed from the SECARB Cranfield Project:

1. Evaluation of aquifer mineralogy is important. If CO_2 should leak into the aquifer, the presence of even minor amounts of carbonate minerals has a strong impact on both the risk to aquifer quality and detectability of leakage (Yang et al., 2014a).
2. Simple batch reactions using aquifer sediments and introduced CO_2 can provide information about the possible rock-water reactions that may occur if CO_2 unexpectedly enters the aquifer. Risk can be better constrained by conducting tests in situ (i.e., a push-pull test), which are of high value in design of a monitoring program (Yang et al., 2013b; Yang et al., 2015a; Yang et al., 2014b; Yang et al., 2014c; and Yang et al., 2014d).
3. Parameters most sensitive to CO_2 leakage in all rock types include dissolved CO_2 and/or dissolved inorganic carbon in groundwater (Yang et al., 2014a; Yang et al., 2014b; and Yang et al., 2014c). Determining accurate CO_2 species requires high-quality sampling techniques to prevent losses by outgassing.
4. The cost of monitoring an aquifer depends on aquifer characteristics. A relatively simple model can provide input on the spacing of wells needed to provide monitoring (Yang et al., 2015a; and Yang et al., 2015b). This cost will vary from site to site.

CASE STUDY 5.3 — **SWP**

SOUTHWEST REGIONAL PARTNERSHIP ON CARBON SEQUESTRATION (SWP)

Creating an Accessible and Secure Characterization Material Data Archive

As a flood of data and interpretations began to inundate the Southwest Regional Partnership on Carbon Sequestration (SWP) during the first two years of its Development Phase project, it became apparent that sharing data among organizations and companies with different data security protocols required a common framework. E-mailing documents can result in multiple versions, improper sharing, and unsuitable file-size limitations. File transfer protocol (FTP) servers and cloud-based file-hosting options were considered. However, at the time of project implementation these options lacked features that were necessary for sharing data within the security constraints of government and commercial partners. The table below provides a generalized list of some of the data that is collected for a characterization project and Figure A demonstrates some of the wide variety of data types that might be encountered.

SWP adopted Velo, a Pacific Northwest National Laboratory (PNNL)-developed online database and communication software package, to accomplish data sharing and discussions about data and subsequent interpretations (Figure B). Velo provides a customizable and collaborative knowledge-management and analysis framework based on commercial-grade products and an integrated environment for secure, collaborative data and knowledge management, analysis, visualization, and sharing. Velo has an integration framework allowing project deployments to integrate a variety of existing analytical tools including workflows, scripts, analysis, and visualization tools. The software ensures a secure and remote backup of key project datasets, interpretations, and documents that are readily accessible to any account holder in SWP. To make the most of this data resource, the use of metadata and common formats is encouraged.

Data Collected for Characterization

Data Types	Kinds of information
Well data	Logs, core images, test data, sample data, physical samples
Seismic data	3-D, VSP, Crosswell,
Field data	Geocellular models, simulations, sample data, GIS data
Publications	Abstracts, presentations, publications, technical papers
Images	Photos and illustrations

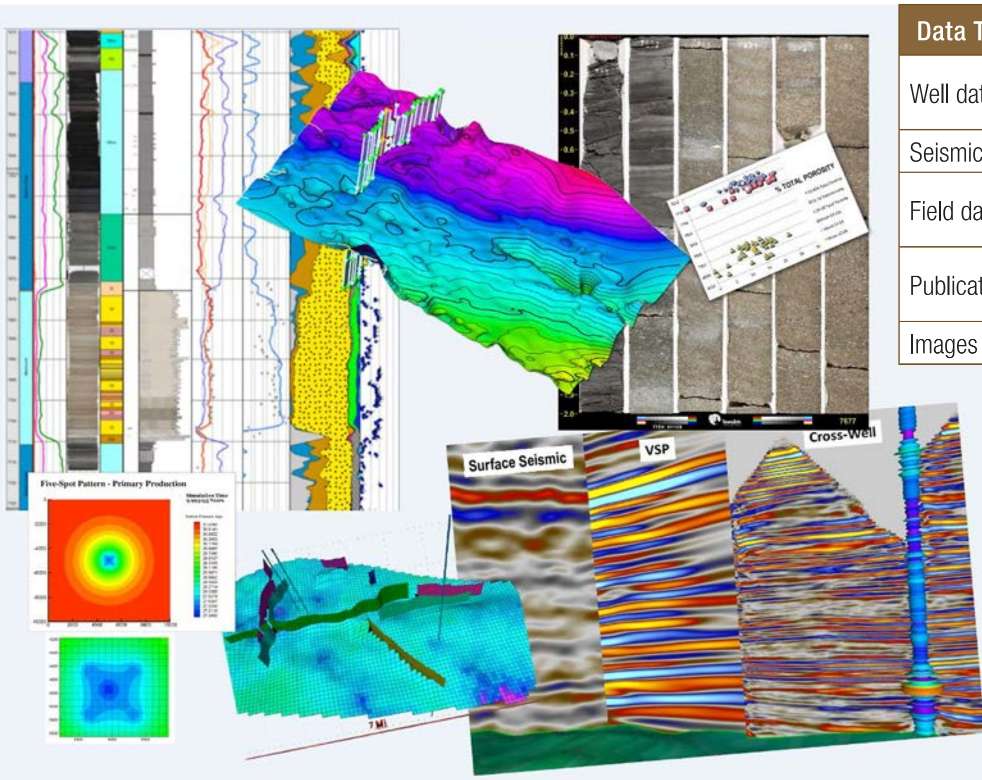


Figure A: Physical core, core analysis data, log data, 2D and 3D seismic data, VSP data, and reservoir simulations are just some examples of the data that must be both archived and made accessible to project partners.

CASE STUDY 5.3 — SWP (continued)

SOUTHWEST REGIONAL PARTNERSHIP ON CARBON SEQUESTRATION (SWP)
Creating an Accessible and Secure Characterization Material Data Archive (continued)

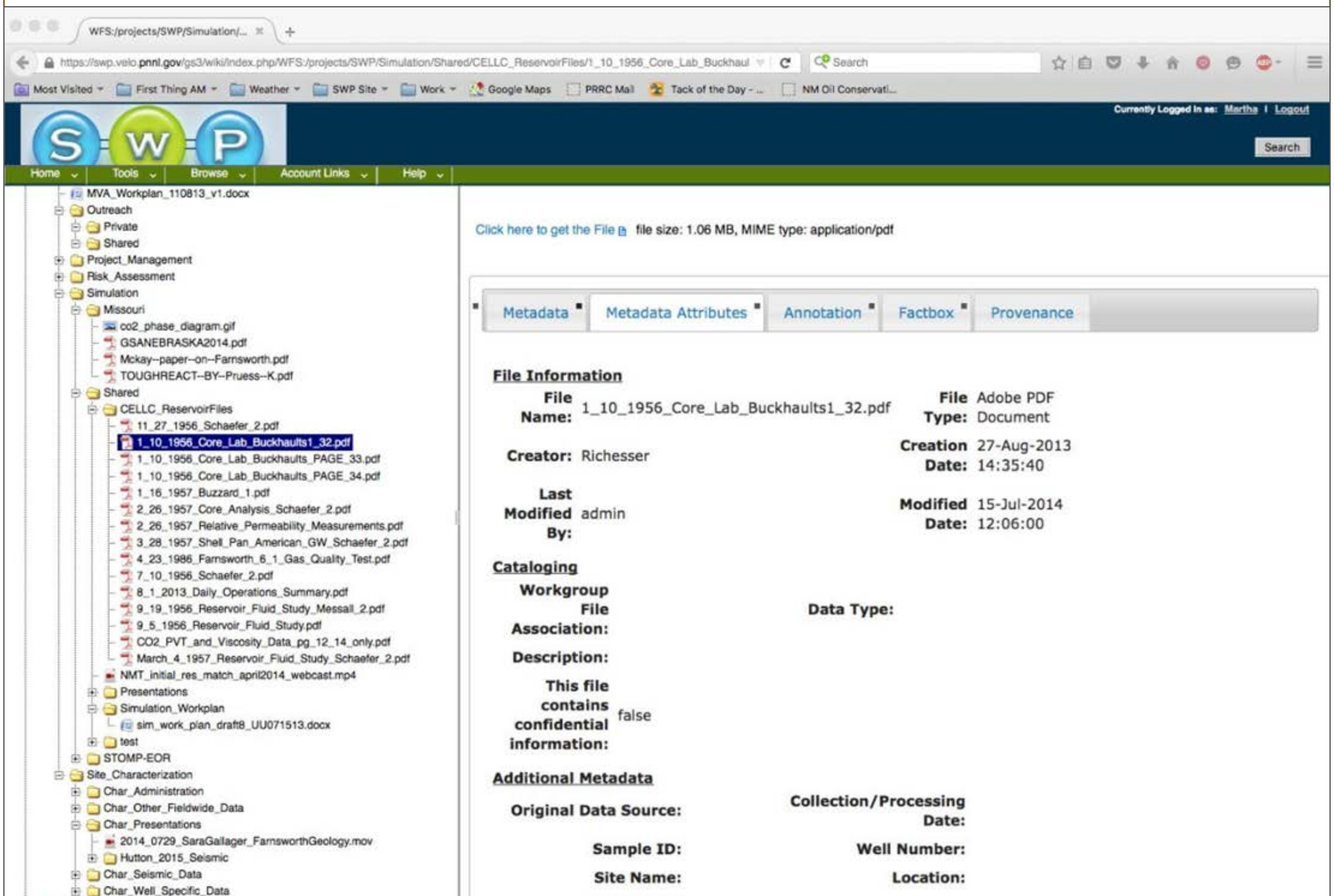


Figure B: Velo is a web-based interface to the data archive that has been used by SWP. As the project progresses, archive and data management become more important, and needs may evolve through the life of the project.

CASE STUDY 5.4 — **SECARB**

SOUTHEAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (SECARB)

Formation Evaluation – Estimating Initial Porosity and Permeability for the Paluxy Formation

The Southeast Regional Carbon Sequestration Partnership (SECARB) Development Phase Citronelle Project is located in the Citronelle oilfield in Mobile County, Alabama. Prior to well drilling, little reservoir data existed on the Paluxy sandstone injection targets. Core data were unavailable to provide porosity and permeability values. The nearest wells with density/neutron porosity logs were located more than four miles away from the proposed injection site. The only available field data for the proposed injection site consisted of an array of vintage geophysical well logs for most drilled wells. However, these well logs included only spontaneous potential (SP), induction (analogous to deep resistivity), and short normal resistivity curves.

To make best use of the available data, existing deep resistivity log data were used to calculate porosity and characterize the average Paluxy reservoir properties in the proposed injection area. Resistivity porosity can be calculated using the standard Archie equation for calculating water saturation (S_w) in "clean" (shale free) sandstones and carbonates (see figure below). The Archie relationship was originally developed as a method to determine hydrocarbon versus non-hydrocarbon bearing zones using the formation's true resistivity (R_t) (Archie, G.E., 1942; Asquith and Krygowski, 2004). However, in a clean (shale-free) water-bearing formation (i.e., a S_w approaching 100 percent), the equation can be rearranged to calculate porosity.

$$\phi = \left(\frac{a}{\left(\frac{Rt}{Rw}\right) \times Sw^n} \right)^{1/m}$$

Where:

Sw = water saturation
a = tortuosity factor
m = cementation factor
Rt = true formation resistivity as derived from deep resistivity (ohm-m)
Rw = resistivity of the formation water
Φ = porosity (percent)
n = saturation exponent

The standard Archie equation for calculating water saturation in "clean" sandstones and carbonates.

Applying the above resistivity porosity algorithm to the wells with available porosity logs provided an opportunity to benchmark porosity values in the field. The Archie parameters and assumed inputs for R_w and S_w were then slightly adjusted to calibrate the resistivity porosity to the measured neutron-density porosity in these wells. This calibrated resistivity porosity equation was then applied to the vintage test site well logs field-wide. Calculated Paluxy sandstone porosities for the test site ranged from 16 to 22 percent.

To extrapolate the permeability of the Paluxy formation's major sand bodies over the study area, a regional permeability-porosity relationship was established. All publicly available core permeability data from the Paluxy formation in the region was supplied by the Geological Survey of Alabama. These data were extracted primarily from sidewall core samples. The closest available Paluxy core data to the test site were comprised of data from the Tensaw Lake, Latham, and Pleasant Home oilfields, all located more than 20 miles to the east.

Application of a core porosity-permeability crossplot to the resistivity porosity resulted in an average permeability of 88 millidarcies (mD). However, core-calibrated log results for the Paluxy target sandstones acquired later from the newly drilled Anthropogenic Test wells yielded an average porosity of 19 percent and an average permeability of 280 mD. Comparison of these results indicated that the permeabilities calculated by regional sidewall core were poor and likely due to sidewall core damage and geologic variation. Despite the sidewall core discrepancies, the results suggest that the resistivity porosity approach may be an appropriate methodology for estimating porosity and reasonably extrapolating permeability in conventional (i.e., clean, high porosity) Gulf Coast target reservoirs.

CASE STUDY 5.5 — **MGSC**

MIDWEST GEOLOGICAL SEQUESTRATION CONSORTIUM (MGSC)

Identifying Multiples in Seismic Reflection Data

The Importance of Zero-Offset VSP

Seismic reflection data is collected not in depth below the surface, but in the length of time a seismic wave travels from its source, reflects from subsurface features, and returns to the sensor. It is important to recognize the depths to different reflective interfaces and formations and to have an accurate model of the subsurface. The optimum way to accomplish this is to use either zero-offset Vertical Seismic Profile (VSP) and/or a check-shot survey. In the Illinois Basin – Decatur Project (IBDP), researchers found that the zero-offset VSP was critical in understanding which reflectors are related to stratigraphic changes. In this area of Illinois, there is a preponderance of seismic multiples that masked the true reflectors and also made any correlation within the Mt. Simon reservoir difficult. Seismic multiples are seismic events that have undergone more than one reflection. Multiples make interpretation difficult, because the reflections may not be real geologic features. The zero-offset VSP and the velocity log were used to identify the key stratigraphic intervals and were important in removing multiples.

CASE STUDY 5.6 — **SWP**

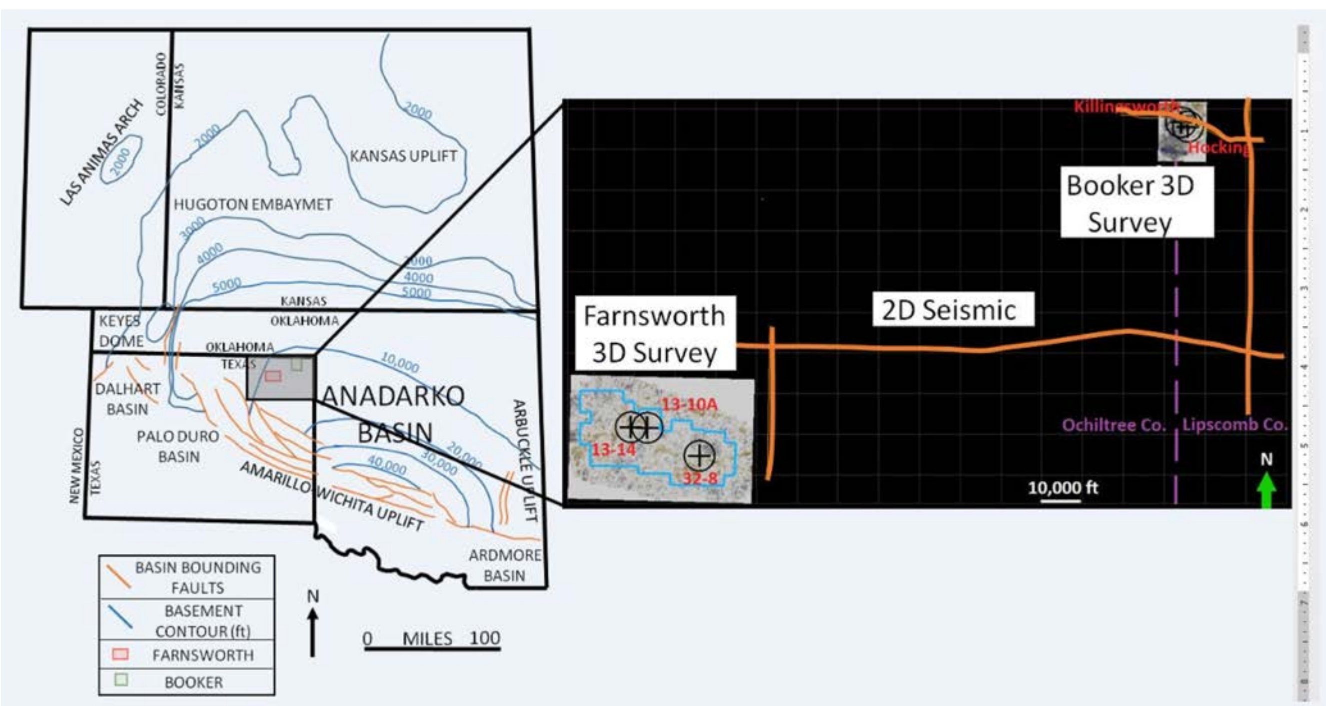
SOUTHWEST REGIONAL PARTNERSHIP ON CARBON SEQUESTRATION (SWP)

Identifying Existing Data and Preventing Multiple Collection of Similar Data

It is important to identify existing datasets that may be acquired at a reduced costs that can add value to existing characterization efforts or prevent the waste of resources from multiple collection of the same existing data.

At Pump Canyon (Validation Phase field project), in San Juan Basin, New Mexico, the Southwest Regional Partnership on Carbon Sequestration (SWP) needed to verify structural containment and the presence of a CO_2 source with limited geological data. SWP identified legacy 2D seismic lines that could be purchased from a vendor (Seismic Exchange International) at a fraction of the cost of acquiring new data to help make a preliminary evaluation.

In the Anadarko Basin (Farnsworth Unit Project), SWP had a new 3D seismic survey made for the Farnsworth oilfield that provided excellent local data. One of the goals of the project was to create a more regional model that would extend to other geologically similar reservoirs in the Anadarko Basin of the Texas and Oklahoma panhandles. To aid in this effort, the operating partner, Chaparral Energy, offered the use of an existing 3D seismic survey taken in the Booker Field (see figure below). To do basin-scale petroleum system modeling, the two surveys needed a common data tie, because the two fields were 30 miles apart. Existing legacy 2D seismic lines connecting the two fields were purchased from Seismic Exchange International at a fraction of the cost of acquiring new data. Well data, check-shot surveys, and logs from wells at the Booker field were also provided by Chaparral. The additional existing data has allowed SWP to create an integrated interpretation of two 3D datasets and is expected to greatly enhance the existing characterization effort.



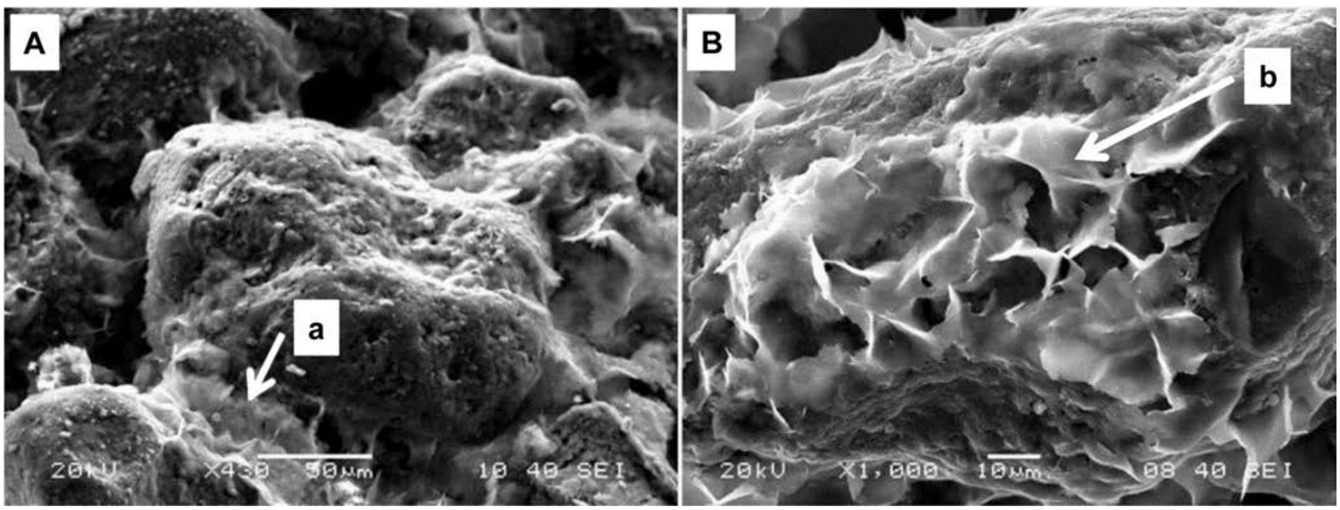
Site of the Farnsworth Unit field project, showing the new survey at Farnsworth, which was connected to an existing survey at Booker Field via existing 2D seismic lines.

CASE STUDY 5.7 — **MGSC**

MIDWEST GEOLOGICAL SEQUESTRATION CONSORTIUM (MGSC)

Determining the Petrology of the Reservoir and Seal

The understanding of the mineralogy, porosity, and pore throat geometry is important in evaluating the rock/CO_2 interactions of both the reservoir and the seal. Petrologic studies are also critical in understanding and predicting the flow characteristics of a CO_2 plume (Roy et al., 2014). This type of analysis requires detailed petrography and modeling of the reservoir under reservoir pressures and temperatures. For example, laboratory experiments were conducted to evaluate how exposure to CO_2 might alter the reservoir rock and seal in the Illinois Basin - Decatur Project (Yoksoulian et al., 2013). The Mt. Simon Sandstone was analyzed pre- and post-injection to determine physical, geochemical, and mineralogical changes (see figure below). They observed decreased amounts of clay surrounding quartz grains after six months of immersion in acidified brine. The brine samples were also analyzed for inorganic anions and metals. The Geochemist's Workbench™ was used to match geochemical data with experimental data. It is important to do both numerical modeling and experimental modeling to calibrate and determine rates of change.



SEM images of pre- (A) and post-reaction (B) Mt. Simon Sandstone sample 6,757.6 ft. (2,059.7 m). Each image shows a clay coated quartz grain. Arrow (a) shows massive clay filling pore space between two quartz grains in the pre-reaction sample. Arrow (b) shows illite filling the pore space and the massive clay now non-existent or present in trace amounts in the post-reaction sample.

(Yoksoulian et al., 2013)

CASE STUDY 5.8 — **SECARB**

SOUTHEAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (SECARB)

Characterizing Geologic Units above the Injection Zone

Site selection typically focuses on the reservoir and overlying reservoir seal. However, characteristics of the intervals between the injection zone and the protected near-surface resources have an important additional impact on the success of the project. These "overburden" intervals are typically less studied or understood than the injection zone and, therefore, need focused evaluation during site characterization.

Overburden is typically composed of alternating high- and low-permeability layers. This interbedding limits risk of out-of-zone migration. Models show that vertically migrating fluids in contact with the overburden rocks will migrate into permeable layers before advancing upward, which retards and attenuates leakage (Nordbotten et al, 2005; Porse, 2013). The role of the permeable strata is to complement additional low-permeability zones, a combination sometimes referred to as secondary traps. If the role of the layered confining system is considered to be retardation and attenuation of vertical migration, risk of project failure can be greatly reduced. Monitoring effective attenuation can be accomplished by measuring pressure in the injection zone (IZ) and in one or more above-zone monitoring interval (AZMI). Pressure response of the IZ and AZMI can be modeled to assess and quantify hydrologic isolation or connectivity (Sun and Nicot, 2012; Zeidouni and Pooladi-Darvish, 2012; Zeidouni, 2014; Strandli et al., 2014).

Zones in the overburden can add risk to leakage scenarios if they themselves contain protected resources or if they are linked to fast paths to the surface. An example of such an added risk was present at the Southeast Regional Carbon Sequestration Partnership (SECARB) site at Cranfield, where a zone of shallow hydrocarbon production in the Wilcox Formation at approximately 3,000 feet overlies parts of the area and where CO_2 injection and CO_2-EOR were conducted at 10,000 feet. If CO_2 migrated up to the Wilcox Formation, risk would have been increased both by possible damage to hydrocarbon resources and by fast transmission of CO_2 to atmosphere through production wells and other unprepared wells. Past or ongoing use of overburden for extraction or disposal (e.g., wastewater or water for secondary recovery) can create complex pressure and fluid conditions that may mask or mimic leakage and decrease monitoring effectiveness or limit monitoring options.

At the SECARB Development Phase Cranfield Project, the research team developed a program of continuous pressure and intermittent geochemical surveillance of one AZMI to test the role of overburden for monitoring. The selected AZMI was 10-meter thick sandstone of the upper Tuscaloosa Formation approximately 300 feet above the lower Tuscaloosa D-E injection zone. Three wells were instrumented with both IZ and AZMI downhole pressure gages installed on wireline and connected to surface read-out (SRO) for both zones. In addition, geochemical samples were extracted from both IZ and AZMI perforations. Outcomes of the program showed that the approach is favorable for the intended purpose (Meckel and Hovorka, 2009; Tao et al., 2013; and Kim and Hossieni, 2014).

A number of lessons learned were provided from these instrumented wells. Most important, success of an AZMI monitoring program is highly dependent on pre-installation characterization. Good information on hydrologic properties of the AZMI, including thickness, permeability, lateral variability, and boundary conditions, are essential to modeling the sensitivity of an AZMI installation to leakage. At Cranfield, one difficulty in fluid sampling occurred because the area of the AZMI into which one well was drilled had low permeability, so producing long enough to purge the wellbore and obtain a clean sample was cost-prohibitive. In addition, the complex multi-zone AZMI installations experienced problems obtaining high-quality data. Creating and maintaining open perforations to the AZMI was a problem because standard well management techniques were not possible in these complex wells. Effective isolation of the AZMI zone from the IZ was a recurrent problem for geochemical sampling.

In future AZMI installations, recommendations include: (1) incorporate geologic characterization using core, wireline logs, and 3D seismic interpretation; (2) conduct hydrologic characterization using single and multi-well interference tests; (3) utilize wells dedicated solely to AZMI monitoring to avoid interference with IZ fluids and pressure and, in addition, to support the use of standard well management and maintenance procedures, and (4) design multi-wells dedicated AZMI installations to allow coverage of the area and estimation of location for any detection.

CASE STUDY 5.9 — **MRCSP**

MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

Evaluating Hydrogeological Data: Example from MRCSP Regional Characterization Efforts

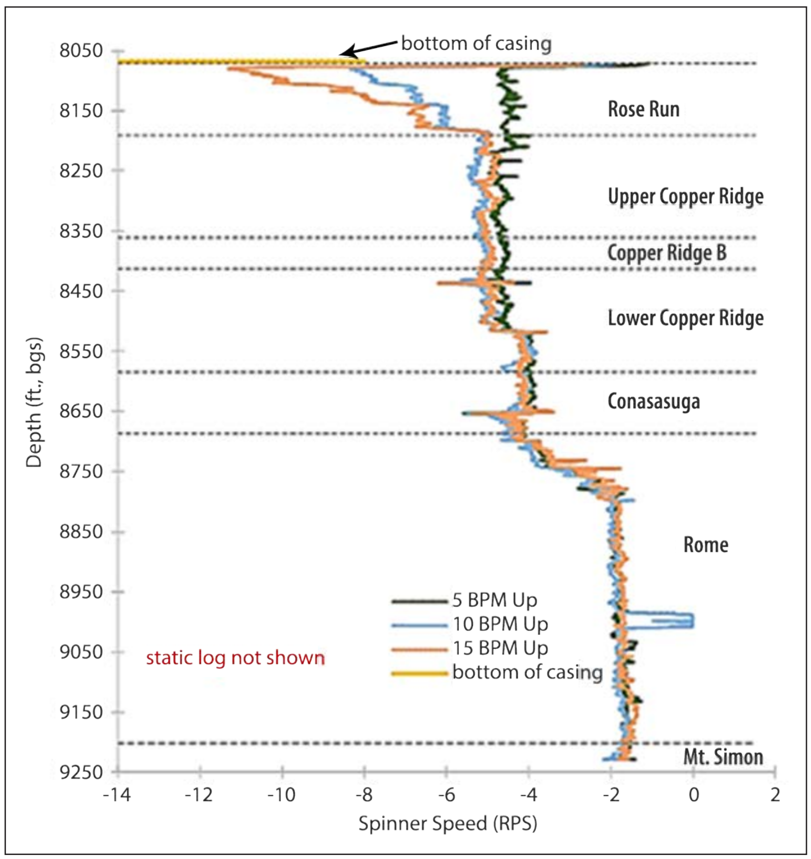
Hydrologic-test data for five brine-disposal wells located in eastern Ohio were used to make inferences about the potential efficacy of Cambrian-Ordovician strata for CO_2 storage (Kelley et al., 2015). The study involved working with brine-disposal well owners to conduct hydrologic testing or to obtain data from hydrologic tests already performed.

Flow-meter logging data, available for all five wells, was the primary data used to identify depth intervals of injection zones. The flow-meter logging test involved a mechanical borehole flow meter (spinner-meter) that was first lowered/raised across the open-hole interval under static-flow (no injection) conditions and then under dynamic-flow conditions while injecting brine into the well (see figure below). Usually, multiple dynamic passes were made to obtain results for different injection rates. One well also had a repeat temperature log that was useful for corroborating the spinner-meter logging results.

Pressure fall-off data were available for three of the five wells. For pressure fall-off testing, bottom-hole pressure was recorded while brine was injected into the well in a controlled manner and following cessation of injection during the fall-off period. The pressure fall-off data were analyzed using pressure transient analysis and other techniques to determine a composite transmissivity of the injection zones identified with the flow-meter logging test.

Three potential reservoir zones were identified within the same general stratigraphic position in more than one well suggesting that these zones may be laterally continuous across some or all of the 30-mile section, including the Rose Run, Lower Copper Ridge, and Lower Conasauga and/or Upper Rome. The composite transmissivity of the reservoir zones, an indicator of injectivity, varied from very high (~200,000 millidarcies [mD]-ft) in the western half of the section to medium (~6,500 mD-ft) on the eastern end of the section.

The results of this study suggest that there are potentially viable CO_2 storage reservoirs within the Cambrian-Ordovician strata of eastern Ohio. Injectivity appears mostly favorable. The reservoirs need to be mapped to determine their extent and potential CO_2 storage capacity.



Example Flow-Meter Logging Data. During open borehole test, spinner speed readings for flow conditions (static, low-barrels per minute [BPM], high-BPM runs) were analyzed to determine vertical distribution of permeable zones capable of receiving injected fluid.

CASE STUDY 5.10 — **MRCSP**

MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

Developing Static Earth Models Using Existing Seismic Data

The Michigan Niagaran reefs used for CO_2 storage as part of the Midwest Regional Carbon Sequestration Partnership (MRCSP) Development Phase project are located in the Northern Reef Trend in Otsego County, Michigan. The Northern Reef Trend is composed of Silurian-age Niagaran Pinnacle Reefs, which are part of an extensive, shallow, shelf-carbonate depositional system. There are approximately 800 fields and the reservoir facies consist of porous and permeable dolomite.

The development of static earth models (SEMs) have been critical for characterizing volumetric properties and porosity distributions within the complex carbonate reservoirs. That involves full integration of wireline, whole core, seismic, production, pressure, and monitoring data. Three-dimensional seismic data greatly increases the chances of discovering reefs, properly locating wells, defining reef boundaries, and understanding property distributions within the reefs.

Seismic data was procured through collaboration with an industry partner and analyzed using Petrel software. The seismic data was integrated with the well data to provide a robust interpretation of the geologic structure. Key horizons were identified, including the Gray Niagaran, Brown Niagaran (reef), A1 Carbonate, and A2 Carbonate. These were identified by the high angles of the reef flanks and the dispersive effect typically seen due to the steep angles. Once the horizons were picked, they were used to generate the structural framework (boundaries) of the reefs as input in SEMs (see figure below). The main study reef is in the middle of the image, with additional reefs distinguishable. The relief in the main study reef is approximately 300 feet, which is consistent with what is seen in the wireline logs. As more data becomes available, the interpretation and the model will be updated to help refine the reef boundaries.

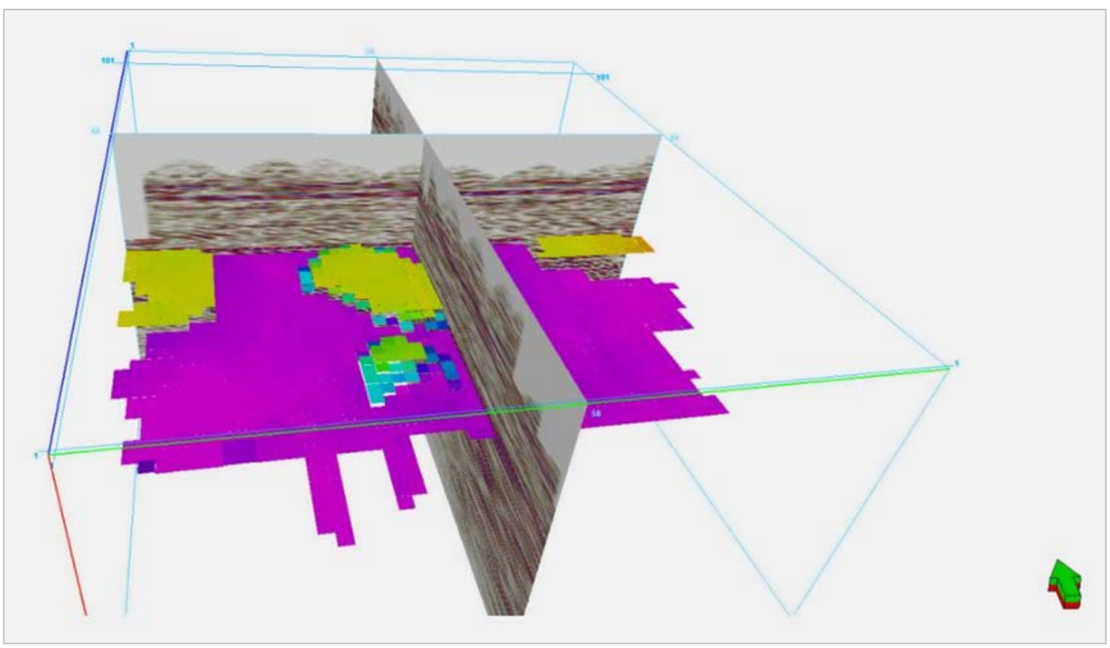


Image of an interpreted 3D seismic volume. The pinnacle reefs are represented by yellows and greens due to the shorter travel times to the deepest part of the Brown Niagaran (pink).

CASE STUDY 5.11 — MGSC

MIDWEST GEOLOGICAL SEQUESTRATION CONSORTIUM (MGSC)

Delineating Reservoir Properties with Seismic Inversion

Seismic inversion is a methodology of transforming seismic reflection data into a measure of reservoir properties, such as porosity, using existing well control to calibrate the transformation model. The original seismic processing only shows amplitudes (Figure A). At the Illinois Basin - Decatur Project (IBDP), two different methods of seismic inversion processing were attempted. The first inversion (Figure B) was completed with only one well (CCS1). This inversion was completed before multiples were discovered in the seismic reflection data. The second inversion (Figure C) was completed after two additional wells (VW1 and VW2) were drilled at the Decatur site. The two seismic inversions are similar, but the second one is a better match for the well data. The reservoir properties estimated using inversion gives a more detailed look at the variation in reservoir quality and is a necessity when trying to develop a reservoir model to be used as input into a numerical reservoir flow simulation.

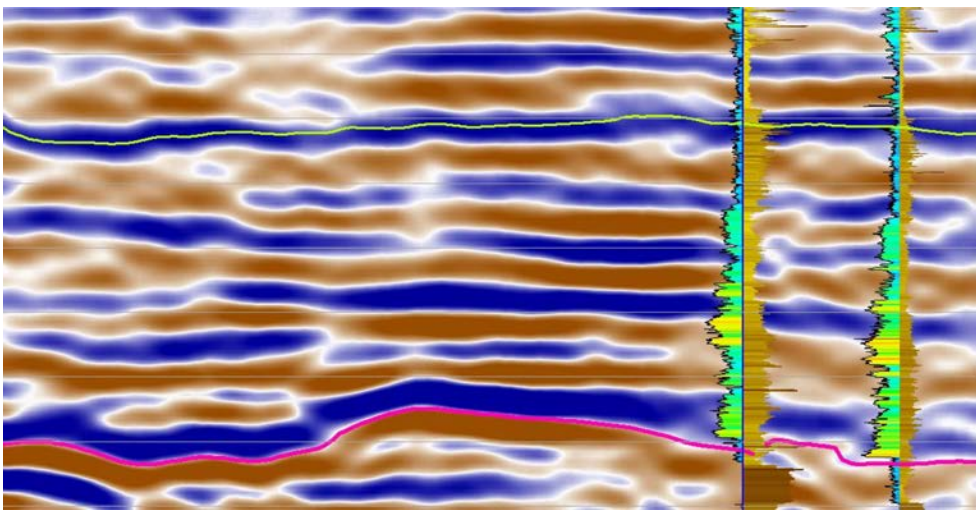


Figure A: Seismic reflection profile across the IBDP site.

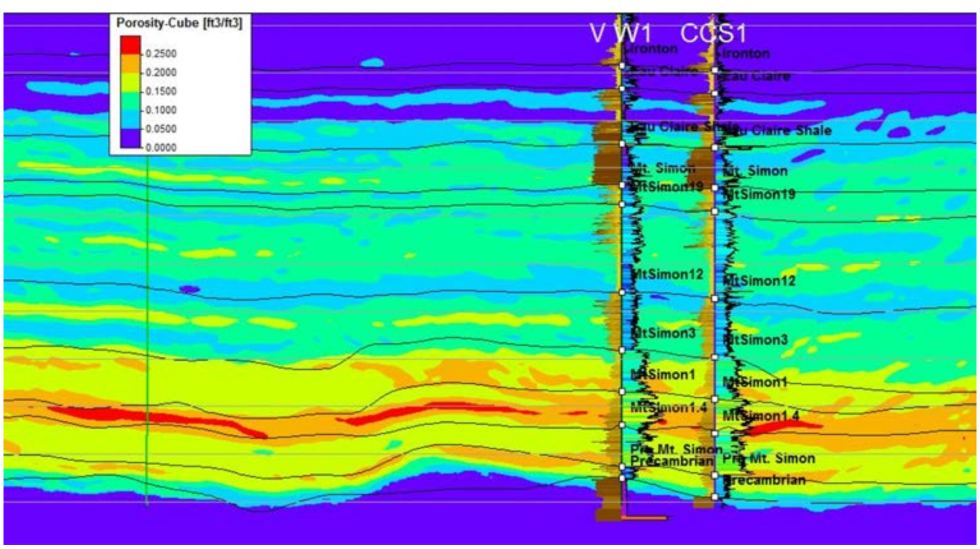


Figure B: Seismic inversion approximately same location as Figure A.
Inversion was before multiple removal and used only the CCS 1 well.

CASE STUDY 5.11 — **MGSC (continued)**

MIDWEST GEOLOGICAL SEQUESTRATION CONSORTIUM (MGSC)

Delineating Reservoir Properties with Seismic Inversion (continued)

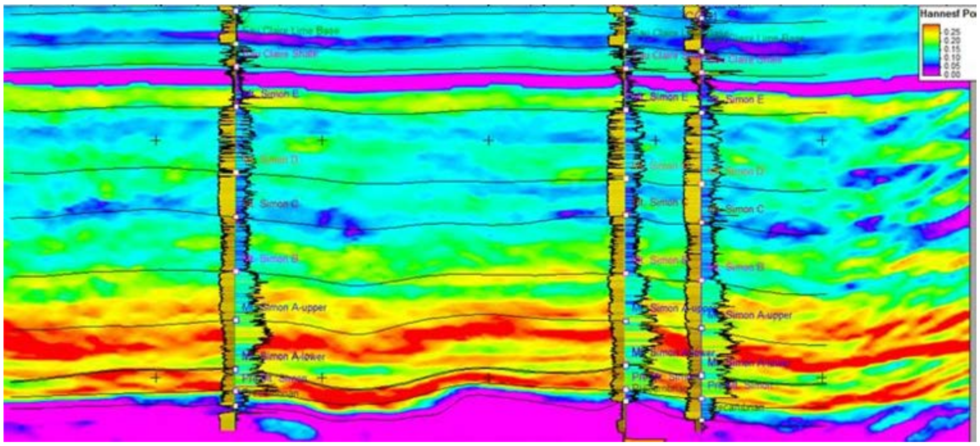


Figure C: Seismic inversion approximately same location as Figures A and B.
Inversion was completed after multiple removal and used all three wells for control.

CASE STUDY 5.12 — **PCOR**

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP

Drilling a New Exploratory Well to Better Understand the Subsurface—An Example from the Fort Nelson Project

The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy and Environmental Research Center (EERC), and Spectra Energy Transmission (SET) investigated the feasibility of a CCS project to mitigate CO_2 emissions produced from SET's Fort Nelson Gas Plant. The complex properties of the carbonate formations at the Fort Nelson project area in northeastern British Columbia, combined with the remoteness and extreme climate conditions of the location, make routine characterization both challenging and potentially misleading. There are two perspectives from which the Fort Nelson project can be considered a good case study for baseline geologic characterization. First, because there is a substantial amount of historical data from hydrocarbon exploration and production activities in the Fort Nelson area, the site offers insight into how the data can be evaluated and applied to a CCS project. Second, its remote location, harsh climate conditions, and difficult terrain mean that there are also underexplored portions of the area where major data gaps exist. Based on the results of a first-round risk assessment, the project team recommended that more knowledge of the overall geologic system should be gathered. One activity performed to address this recommendation was the drilling of a new exploration well.

The exploratory well enabled SET to better assess the fundamental geologic characteristics of the seal-sink system, particularly with respect to injectivity, storage capacity, and integrity of containment in the Fort Nelson project area. This additional knowledge was used to develop a more realistic geologic model of the project area, which resulted in an improved understanding of the potential effects and migration of the injected CO_2. Additionally, a second-round risk assessment was performed to provide a more accurate picture of the project's critical risks. Finally, a comprehensive MVA plan was developed to monitor the system and document that the risks are being managed. The combination of an effective risk management framework and an MVA plan will help ensure that the technical subsurface risks are successfully identified and controlled over the lifetime of the project. The knowledge gained from drilling an exploratory well provided stakeholders with insight into approaches and techniques that could be applied to less-explored geologic formations, which is often the case with nonhydrocarbon-producing saline formations.

Drilling the exploration well in the Fort Nelson Project area, northeast British Columbia.

CASE STUDY 5.13 — **MGSC**

MIDWEST GEOLOGICAL SEQUESTRATION CONSORTIUM (MGSC)

Deciding if 3D Seismic Reflection Data Should be Acquired Before or After Drilling the First Well

Long 2D seismic reflection profiles are an absolute necessity when evaluating the suitability of a proposed site for carbon storage. However, if there is limited well control at a proposed site, then the question arises on whether to drill a well through the reservoir or acquire 3D seismic before drilling the well. This is not a trivial question and requires careful evaluation. In the case of the Midwest Geological Sequestration Consortium (MGSC) Illinois Basin - Decatur Project (IBDP), there was no well control within a 30-mile radius of the proposed location. The 2D seismic showed no resolvable faulting. However, there was not enough velocity control to identify the reservoir or the Precambrian basement below the Mt. Simon Sandstone. A decision was made to drill a well based on 2D seismic reflection data interpretations, because a 3D seismic reflection program including acquisition, processing, and interpretation was cost-prohibitive at that stage of the project.

CASE STUDY 5.14 — **SECARB**

SOUTHEAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (SECARB)

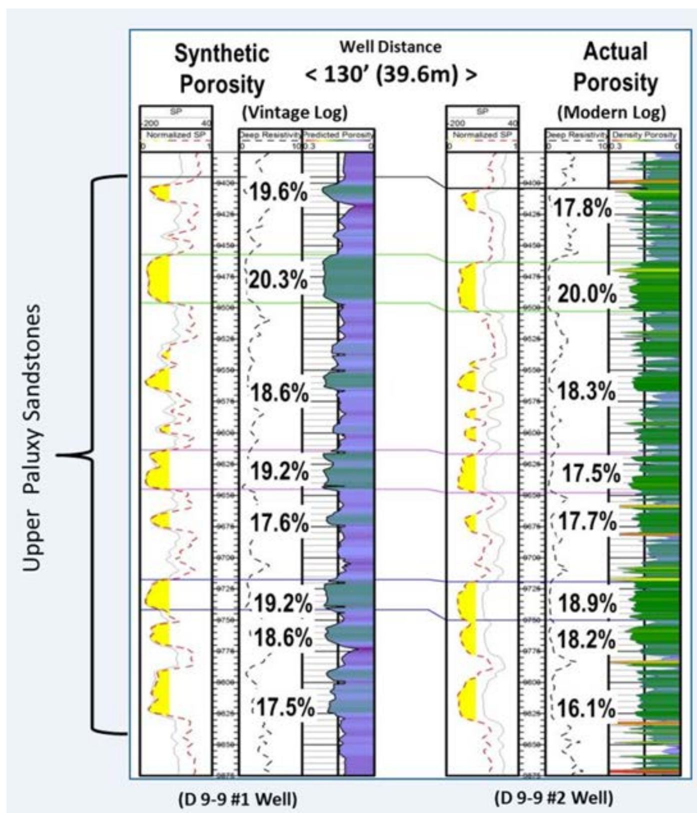
Maximizing the Use of Existing Geologic Data—Example from the SECARB Development Phase Field Project (Neural Networks)

The Southeast Regional Carbon Sequestration Partnership (SECARB) Development Phase project site is located in the historic Citronelle oilfield in Mobile County, Alabama, on the crest of a geologic dome structure. More than 700 existing wells penetrate the target saline storage reservoir, the Paluxy formation, in addition to several other prospective saline reservoirs. Geophysical well logs are available for most wells in the oilfield. However, due to their vintage, a majority of these well logs do not include a measurement of porosity.

As part of the SECARB Citronelle field project, three new wells were drilled proximal to three abandoned and previously logged wells. Each new well was logged with a comprehensive suite of modern geophysical tools. Citing the application of pattern recognition research, neural networks were utilized to generate synthetic porosity data from the vintage logs by leveraging the modern log porosity measurements. Synthetic neural networks are a well-established method for pattern recognition, and provide a useful tool to extrapolate truth-grounded synthetic datum for a related data set (Hopfield, 1982; Bishop, 1995; Wong et al., 1998; Al-Bulushi et al., 2012; Das et al., 2012). The application of neural networks provides the opportunity to place constraints on porosities of various lithologic units in the Citronelle Dome, and to interpolate them over the field.

The data used to develop the neural network includes the spontaneous potential (SP) and induction and short normal resistivity curves from the vintage, digitized raster logs of the abandoned wells, and the density porosity from the modern well logs in the new, associated wells. Neural network training was conducted using MATLAB's neural network toolbox by applying a two-step process: (1) training the neural network, and (2) validating the neural network. First, this process completes the pattern recognition component to develop output parameters for the synthetic data, and then assess the algorithm's association to ensure the quality of the synthetic neural network data. Each step is essential to substantiate the applicability of the method's use over the entire study area.

A comparison of a synthetically generated porosity curve from a vintage well log with the associated modern density porosity log from the new well is shown in the figure below. The data correlation varies among stratigraphic horizons between the two wells, but there is a marked overall similarity. While some differences are observed among zones, these may likely be caused by the low resolution of the vintage logs or local geologic variation. With this promising result, the trained model is applied to map porosity trends over the Citronelle Dome area using the scores of vintage raster logs.



The synthetic porosity curve for the D-9-9 #1 well on the left as compared to the actual porosity (density) curve measured in the D-9-9 #2 well on the right. Comparison of associated stratigraphy shows relatively good agreement of synthetic data with measured data.

CASE STUDY 5.15 — **SECARB**

SOUTHEAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (SECARB)

Increasing the Ease and Accuracy of Environmental Monitoring—Lessons from the Cranfield Project

A critical element of environmental monitoring at geologic carbon storage sites is the ability to quickly and accurately assess the origin of any suspected leakage. For example, soil gas CO_2 anomalies identified through routine monitoring or visible changes to the environment will need to be attributed either to leakage or to one of the many other natural and anthropogenic factors that could create similar effects. Source attribution of a potential leakage signal in the near-surface must be timely and accurate. Research at the Cranfield site has identified screening methods that can be used to quickly indicate whether leakage can be ruled out, or whether further assessment is required.

Environmental monitoring at the Cranfield site was targeted to a soil-gas anomaly detected near a modern gravel well pad constructed around a 1950s-era plugged and abandoned well in the process of being repurposed for CO_2-EOR. In reference to a co-assessment of plants, pit, P&A well, and well pad, this array is informally called the "P-site." Soil-gas monitoring at the P-site and at a nearby background site continued for more than five years. A process-based ratio analysis of data from the P-site indicated an exogenous origin for the gas anomaly (Romanak et al., 2012), suggesting it was a potential leak, but further investigation using radiogenic carbon (^{14}C) indicated that the methane (CH_4) was from a very young source, significantly shallower than, and unrelated to, the injection zone. Thus, the anomaly was not attributed to leakage.

This research indicates that lengthy baseline or background assessment over time is of limited utility for leakage detection. Instead, the use of ratios of various gases (nitrogen [N_2], oxygen [O_2], CO_2, and CH_4), or the use of ^{14}C in combination with stable carbon isotopes, can more accurately and more reliably distinguish naturally occurring vadose zone gases from anomalous gases and does not require prolonged baseline measurements over time.

In light of this finding, and using methods based on ratios (e.g., Trium, 2011; Romanak et al., 2014; Dixon and Romanak, 2015; Risk et al., 2015), the research team observed that a "one-time characterization" at several locations within an area of review is a more accurate and cost-effective approach to leakage detection than the complex statistical analysis and comparison with years of baseline data. This finding represents a significant advance in the potential of near-surface monitoring to separate signal from noise, respond in cases of public leakage claims, and quantify CO_2 release in cases of actual leakage.

CASE STUDY 5.16 — **MGSC**

MIDWEST GEOLOGICAL SEQUESTRATION CONSORTIUM (MGSC)

Site Characterization for the Illinois Basin – Decatur Project

Geophysical logs and petrological analysis of newly acquired cores in the Illinois Basin – Decatur project resulted in major advances in subtle, but important, differentiation between the sub-units of the entire Mt. Simon Formation. Through careful analysis, it was discovered that some of the sub-units within the Mt. Simon Sandstone actually control pressure transmission and CO_2 migration within the formation. Careful analysis of geophysical logs and newly acquired cores were essential to understanding the Mt. Simon sub-units and their effort on pressure transmission and CO_2 migration within the formation.

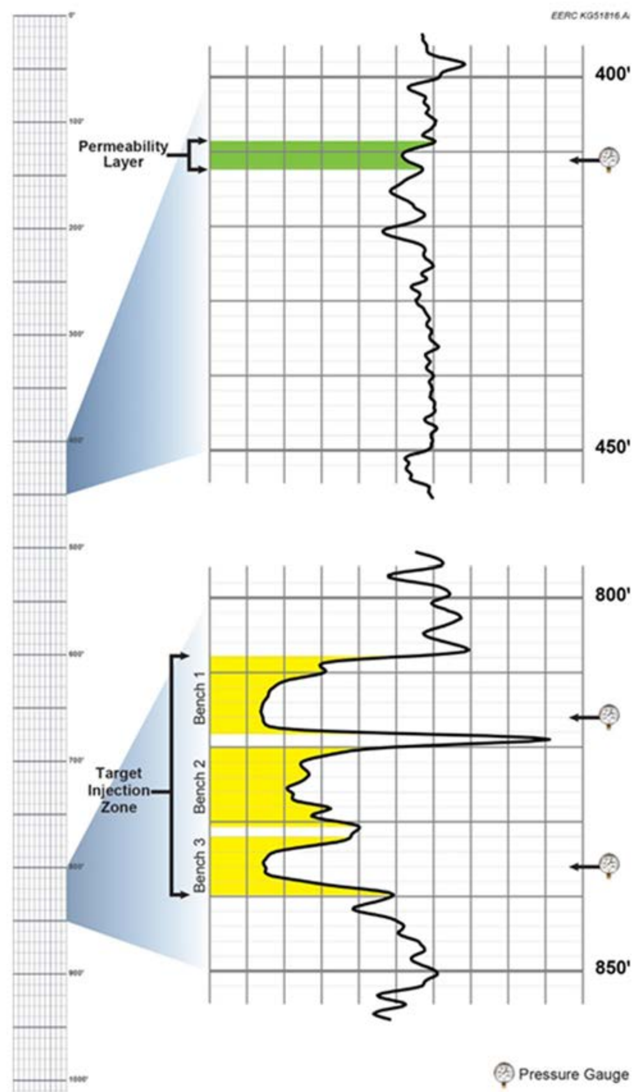
CASE STUDY 5.17 — **PCOR**

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP

Formation Pressure Testing for Reservoir Analysis

The PCOR Partnership conducted formation pressure testing for a monitoring and characterization well at one of its geological CO_2 storage sites. The formations tested, using wireline logging tools, showed 1) partially isolated benches and 2) flow compartmentalization. Initial gamma ray (GR) showed distinct, partially isolated benches within the sandstone. Based on these initial data, a wireline formation pressure-testing tool was used to confirm that partial isolation existed between the benches. The formation pressure buildup was monitored following a small amount of production within the wireline formation pressure-testing tool. The formation pressure-testing tool ultimately identified three isolated benches in the target injection zone, determined by slow pressure buildup between the benches. These tests also confirmed a permeability layer above the target injection zone, which allowed monitoring above the injection zone and which was later confirmed with sidewall cores showing alternating sequences of sandstone separated by shale.

The results of the formation pressure testing led to the installation of two different pressure gauges within the target injection zone. Although, geologically, all the benches exist within the same target injection zone, the partial isolation of each bench could potentially result in different injection rates/pressures across each bench, thus highlighting the utility of multiple pressure gauges. The results also led to the installation of a pressure gauge within the permeability layer above the target injection zone. The formation pressure testing ultimately resulted in the decision to perform permanent downhole monitoring in the well, where pressure has been continuously monitored at the three different partially isolated benches since 2012.



CASE STUDY 5.18 — **SECARB**

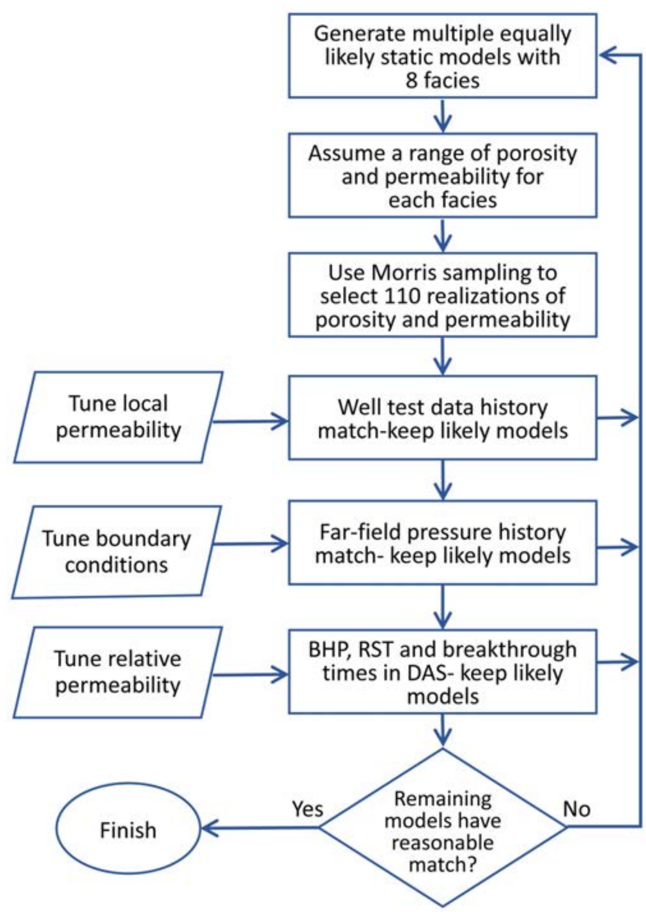
SOUTHEAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (SECARB)

Integrating Data for Dynamic Modeling—Cranfield Project

Legacy data from mid-20th century petroleum operations at Cranfield, Mississippi, indicates that the lower Tuscaloosa reservoir has very low lateral continuity. Consequently, initial characterization focused on defining a robust static model of the reservoir. Datasets (wireline data and whole core from new commercial wells) indicate that the Tuscaloosa comprises amalgamated fluvial point-bar and channel-fill deposits. Such strata are inherently heterogeneous at field and intermediate scales. The facies geometry and stratigraphic architecture of fluvial strata exert important controls on fluid flow (Lu et al., 2012; 2013). Characterization of permeability distribution of fluvial systems using subsurface data is usually challenging because of a high degree of lateral and vertical heterogeneity. At Cranfield, dense geophysical and geochemical data collected downhole, above-zone, and near-surface allowed calibration of reservoir modeling to measured reservoir responses. Integration of the various datasets into a single reservoir model was challenging, and no single model was able to capture all the necessary physics and uncertainty in reservoir parameters. Consequently, a probabilistic approach was used in the Cranfield modeling work to find the best statistical models that could match most of the collected data (Hosseini et al., 2013). This approach in data integration dynamic modeling was based on stochastic reservoir modeling in multiple, sequential steps. Modeling began with single-phase, small-scale data obtained from a well-test experiment so that certain model parameters could be refined – specifically, absolute permeability and porosity. Other uncertain parameters were relaxed (e.g., boundary conditions) because the analysis was focused only on several hours' worth of data. For this period of time, boundaries would not affect numerical simulation results. A range of possible values for permeability and porosity was assumed and a sampling method was used to draw 110 realizations. The field data were compared with a well-test experiment numerical simulation. At the end of this step, realizations showing poor performances were retired. Only models that successfully passed the first step were used in the second step.

In the second step, the global reservoir response was evaluated addressing boundary conditions and global reservoir connectivity and focusing on pressure rise in the water leg of the Cranfield reservoir because of nearby CO_2 injection. One month's worth of data reflecting this behavior was used to improve understanding of the model's boundary conditions and global connectivity.

In the third step, injection and observation wells' bottom-hole pressures (BHP) were studied. Although the observation wells' BHP gauges malfunctioned for extended periods of time, observation wells' wellhead pressure (WHP) data were available, and a correlation between the WHP and BHP data was developed to estimate BHP of observation wells. The figure below summarizes a step-by-step approach in tuning the reservoir model in Cranfield.



Flowchart of the process used to improve reservoir characterization in this study by the integration of field data.

6.0 CARBON DIOXIDE STORAGE RESOURCE CLASSIFICATION SYSTEM FRAMEWORK

This chapter proposes a resource classification framework for CO_2 storage that is based on a similar framework used in the petroleum industry. It will be valuable in documenting the degree of certainty in an individual site's ability to safely store a defined volume of CO_2, and the rigor involved in appraising and developing individual storage sites. Further, establishing auditable standards for data acquisition, analysis, and interpretation for determining the status of a site helps to reduce the uncertainty associated with storage estimates. This will facilitate use of storage estimates for a variety of purposes, including:

- Establishing well-defined criteria for financial decision-making
- Assessments by governmental agencies to define available storage
- Management of business processes to achieve efficiency in appraisal and injection
- Documenting the value of Storage Capacity in financial statements of publicly traded companies

Several classification approaches have been proposed for CO_2 geologic storage. Adaptation of the PRMS is advantageous because of the many similarities in development of a petroleum exploration and production project and a CO_2 geologic storage project. PRMS is a classification system that has worldwide acceptance and is already familiar to subsurface technical experts such as geologists and reservoir engineers, and operating companies, investors, financial institutions, and government regulators who are most likely to be involved in the CCS industry.

The proposed framework is intended as a starting point. The PRMS evolved over a long period of time, which allowed companies to develop their own competitive approaches to resource estimates. The PRMS has also been influenced by U.S. Securities and Exchange Commission actions. These steps have not taken place in the CCS industry, so it is expected that the terms proposed in this CO_2 storage framework will also evolve over time and with experience. The CO_2 storage framework is intended for use from a commercial perspective, not a regulatory one.

6.1 PETROLEUM RESOURCES MANAGEMENT SYSTEM AS AN ANALOG FOR CO_2 STORAGE

The PRMS (PRMS, 2011) was sponsored by several prominent petroleum associations, including the Society of Petroleum Engineers (SPE), the American Association of Petroleum Geologists (AAPG), the World Petroleum Council (WPC), and the Society of Petroleum Evaluation Engineers (SPEE). It is currently widely used to standardize the definitions of reserves and classify resources in the petroleum industry. Three major classifications of resources in the PRMS are based on degree of certainty as to their existence: (1) Prospective Resources—undiscovered (no wellbores or inadequate tests of existing wellbores); (2) Contingent Resources— most of all necessary data are available but commerciality not established; and (3) Reserves –commercially established sources of petroleum. Sub-classes under each major class express the stage in the exploration, as well as the development process the project has achieved.

The PRMS provides an indication of project status risk as a function of the likelihood the project will move into commercial operation. The PRMS classification framework is shown in Figure 6.1. Definition of terms within the PRMS classification framework can be found in Figure 6.3.

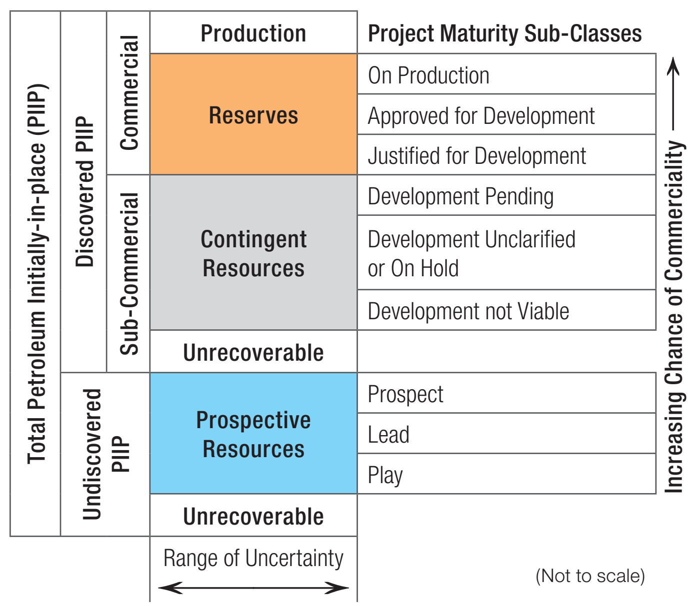


Figure 6.1: SPE/WPC/AAPG/SPEE Resource Classification System

(© 2007 Society of Petroleum Engineers, Petroleum Resources Management System)

6.2 DEVELOPMENT OF A CO_2 STORAGE RESOURCE CLASSIFICATION SYSTEM

The process of identifying suitable CO_2 storage sites is, in many ways, analogous to the exploration for, and development of, oil and natural gas accumulations. A major similarity lies in the effort to characterize connected pore space and the fluids within the pore space. For the upstream oil and natural gas industry, the ultimate goal is to locate hydrocarbon accumulations that contain a sufficient volume of recoverable oil and natural gas to support commercial development. Similarly, for the CCS industry, the goal is to identify formations with pore space of sufficient capacity and injectivity to support commercial storage projects. The stages of the petroleum exploration process involve the same kinds of data acquisition and analyses that are involved in identifying prospective storage sites.

While the analogies between the two efforts are strong, not every aspect of geologic CO_2 storage is fully equivalent to the exploration, development, and production of hydrocarbons. One main difference is that the discovery of a hydrocarbon accumulation is proof that a containment trap exists, while the identification of injectable pore space does not establish that CO_2 can be permanently contained at that site until it has been established that the confining zone will prohibit the vertical flow of CO_2. Another difference is that the petroleum industry "produces" hydrocarbons from a formation, thus removing fluids from known pore volume. CO_2 injection adds fluids to the pore volume and displaces existing saline fluids, which increases pressure in the affected pore volume. Finally, there is virtually no experience in the fledgling CCS industry in defining commerciality.

An adapted version of the PRMS for the classification of geologic CO_2 storage resources is shown in Figure 6.2. This classification system provides a framework for defining storage resources and storage capacity. It also contains a sub-class definition for project maturity.

			Class			Project Status Sub-Class	
Total Geologic Storage	Appraised	Commercial	Storage Capacity			Active Injection	Higher Risk – Project Development – Lower Risk
			1PC	2PC	3PC	Approved for Development	
			Proved Cap	Probably Cap	Possible Cap	Justified for Development	
		Sub-Commercial	Contingent Storage Resources			Development Pending	
			1CS	2CS	3CS	Development Unclarified or On Hold	
			Low	Medium	High	Development Not Viable	
			Un-Injectable				
	Un-Appraised		Prospective Storage Resources			Qualified Site(s)	
			Low	Medium	High	Selected Areas	
						Potential Sub-Regions	

Figure 6.2: CO_2 Storage Resource and Storage Capacity Classification

Modified from SPE/WPC/AAPG/SPEE Resource Classification System (© 2007 Society of Petroleum Engineers, Petroleum Resources Management System)

The CO_2 storage framework is subdivided into "Un-Appraised" and "Appraised" storage potential (Figure 6.2, left-most column). Un-Appraised resources do not have sufficient formation evaluation data (wells, cores, logs, tests, seismic, etc.) to confirm a reservoir with enough capacity, injectivity, and caprock integrity on a site with access to appropriate property rights. Once the site has successfully achieved reasonable certainty with the above criteria, it is termed Appraised. The dynamic classification system, similar to the petroleum classification, further divides Total Geologic Storage into three distinct classes. The Un-Appraised Storage is classified as Prospective Storage Resources and the Appraised potential is classified as Sub-Commercial Contingent Storage Resource or Commercial Storage Capacity. The movement between classes from the Sub-Commercial Contingent Storage Resource to Commercial Storage Capacity would require front-end engineering design (FEED); detailed financials with associated risks and uncertainties quantified; and certainty of a defined regulatory framework.

To better understand the framework, a comparison of general definitions of both classification systems is shown in Figure 6.3, followed by more thorough discussion of each class and sub-class.

6.2.1 PROSPECTIVE STORAGE RESOURCES

Prospective Storage Resources are the pore volume estimates within characterized geologic formations that could potentially be used for CO_2 injection and have been identified through work being conducted by the RCSPs. The quantity and complexity of analyses associated with each project status are in the guidelines from previous chapters. These guidelines should be used to highlight the certainty of analyses results for classifying projects as they mature from Potential Sub-Regions through Qualified Site(s). The results from analyses conducted can decrease project risk but, in turn, increase project costs through the maturation process. Added value of information (VOI) assessments should also be considered for each project site to determine if the data and analysis being collected will influence decisions being made on the project.

Storage resource estimates have a range of certainty within individual parameters used in the calculations, as well as risks of both pore space and project development. Prospective Storage Resource estimates can use analog regional estimates of parameters that are calculated either deterministically or probabilistically. They should be reported as estimates—ow, medium, and high. The Prospective Storage Resources' Project Status is defined into three sub-classes:

Potential Sub-Regions—The project site associated with a sub-regional trend of potential storage sites, similar to the level of data and analysis needed for an exploration "Play." Projects in this category need acquisition of more data and/or additional evaluation. The Site Screening process evaluates these potential Sub-Regions to select a specific Selected Area for continued consideration and further definition of pore space.

Selected Areas – During this evaluation of the project, subsurface evaluation of the potential storage reservoir is poorly defined and requires more data acquisition and further analyses to consider drilling a new well or retesting an existing well. Similar to the "Lead" in the petroleum classification system, during Site Selection, further evaluation of data is incorporated into the initial geologic model framework and Prospective Storage Resources is revised with more confidence and greater certainty with a narrower range of parameter values.

Qualified Site(s)—Evaluations that have taken place up to this point, including Site Characterization, will sufficiently define potential pore space for CO_2 storage. During this evaluation, new data will be acquired to ensure the storage capacity, injectivity, containment, and ability to acquire the rights to store CO_2 at this site. All models will be updated and certainties quantified to sufficiently characterize the storage complex for its ability to safely store a defined quantity of CO_2.

6.2.2 CONTINGENT STORAGE RESOURCES

Contingent Storage Resources have been technically qualified as physically capable of safely storing a determined volume of CO_2, but are not yet commercial due to one or more contingencies. Example contingencies could include a lack of CO_2 market, regulatory framework, and liability. Site-specific contingencies could include the need for development of CO_2 pipeline/infrastructure, securing pore volume rights, awaiting approval of injection permits, or lack of a commercial source of CO_2 to store. During this stage, project development risk decreases, but some risk remains due to the defined contingencies. Also during this stage, all necessary approvals and contracts for long-term injection will be solidified, capital funds will be identified, and implementation will be justified.

Petroleum Industry			CO_2 Geologic Storage		
Class	**Sub-Class**	**Definition**	Class	**Sub-Class**	**Definition**
Reserves		Quantities of petroleum anticipated to be commercially recoverable by application of development projects to know accumulations from a given date forward.	**Storage Capacity**		Quantities of CO_2 anticipated to be commercially stored into formations with known injectable pore space by application of development projects from a given date forward.
	On Production	Development project is currently producing and selling petroleum to market.		**Active Injection**	Commercial-scale development project currently injecting and storing CO_2.
	Approved for Development	All necessary approvals have been obtained, capital funds have been committed, and implementation of the development project is underway.		**Approved for Development**	All necessary approvals and permits have been obtained, capital funds have been committed, and implementation of the development project is underway.
	Justified for Development	Implementation of development project is justified on basis of reasonable forecast commercial conditions at time of reporting and reasonable expectations that all necessary approvals/contracts will be obtained.		**Justified for Development**	Implementation of development project is justified on basis of reasonable forecast commercial conditions at time of reporting and reasonable expectations that all necessary approvals/contracts will be obtained.
Contingent Resources		Quantities of petroleum estimated, as of a given date, to be potentially recoverable from known accumulations by applications of development projects, but which are not currently considered to be commercially recoverable due to one or more contingencies.	**Contingent Storage Resources**		Quantities of estimated CO_2, as of a given date, to be potentially stored into known pore space, by applications of development projects, but which are not currently considered to be commercial projects due to one or more contingencies.
	Development Pending	Discovered accumulation where project activities are ongoing to justify commercial development in the foreseeable future.		**Development Pending**	Discovered pore space for CO_2 storage, where project and site characterization activities are ongoing to justify commercial development in the foreseeable future.
	Development Unclarified or On Hold	Discovered accumulation where project activities are on hold and/or where justification as a commercial development may be subject to significant delay.		**Development Unclarified or On Hold**	Discovered pore space for CO_2 storage, where site characterization and project activities are on hold and/or where justification as a commercial development may be subject to significant delay.
	Development Not Viable	Discovered accumulation for which there are no current plans to develop or to acquire additional data at the time due to limited production potential.		**Development Not Viable**	Discovered pore space for CO_2 storage, which there are no plans for further site characterization and no current development plans at the time due to poor project economics.
Prospective Resources		Quantities of petroleum that are estimated, as of a given date, to be potentially recoverable from undiscovered accumulations.	**Prospective Storage Resources**		Quantities of CO_2 that are estimated, as of a given date, to be potentially stored in undiscovered pore space.
	Prospect	A project associated with a potential accumulation that is sufficiently well defined to represent a viable drilling target.		**Qualified Site(s)**	A project associated with potential pore space for CO_2 storage that is sufficiently well defined to represent a viable storage option and is ready to permit.
	Lead	A project associated with a potential accumulation that is currently poorly defined and requires more data acquisition and/or evaluation to be classified as a prospect.		**Selected Areas**	A project associated with potential pore space for CO_2 storage that is currently poorly defined and requires more data acquisition and further evaluation to be defined as Qualified Site.
	Play	A project associated with a prospective trend of potential prospects, but which requires more data acquisition and/or evaluation to define specific leads or prospects.		**Potential Sub-Regions**	A project associated with a sub-regional trend of potential CO_2 storage project sites, but requires more data acquisition and/or evaluation to define Selected Areas.

Figure 6.3: Comparison of Petroleum Resource Management System and CO_2 Resource Classification

Adapted from SPE/WPC/AAPG/SPEE Resource Classification System
(© 2007 Society of Petroleum Engineers, Petroleum Resources Management System)

Contingent Storage Resources estimates are calculated either deterministically (1CS, 2CS, 3CS) or probabilistically (low, medium, high). Contingent Storage Resources are divided into three sub-classes that focus on development of a commercial project:

Development Not Viable—There are no current plans to develop due to limited commerciality. Storage potential cannot be developed (e.g., due to low rate of return, lack of access to pore space, or the potential geologic storage is too far from the CO_2 source that development is not justified).

Development On Hold—The discovered pore space is of adequate size, but commercial development could be significantly delayed and project activities are on hold. This could be due to a lack of developed capture facilities, or other technical, environmental, political, regulatory, or economical contingencies.

Development Pending—The project is proceeding with project activities moving forward towards commercial development in the foreseeable future at this specific site. It is during this phase of the project that a final "Project Development Plan" is completed and submitted.

The primary difference between the Contingent Storage Resource and Storage Capacity is the commerciality of the project. Based on the petroleum resource classification in the PRMS, the resource should be developed within a reasonable timeframe (usually five years). However, carbon capture and injection technologies are not expected to be broadly commercial until at least the 2020 timeframe. Therefore, it may be premature to finalize guidelines during the start-up periods.

6.2.3 STORAGE CAPACITY

Storage Capacity is the quantity of CO_2 anticipated to be commercially storable by available technology applied at a known site from a given date forward under defined conditions. Storage Capacity must further satisfy four criteria: it must be appraised, injectable, commercial, and remaining (as of the evaluation date) based on the development technology applied. Storage Capacity is further categorized in accordance with the level of certainty associated with the calculated capacity estimates (Proved, Probable, Possible) and may be sub-classified based on the following development and injection statuses:

Justified for Development—The project has been justified on the forecast of commercial conditions, and there is a firm intent (contract) to develop capacity. The project is moving forward on the development plan with the expectation that all necessary approvals and contracts will be finalized (because all necessary approvals and contracts are largely unknown at this time, it would be nearly impossible to place a project in this sub-class until development has started).

Approved for Development—All necessary approvals and permits have been obtained, capital funds have been committed, and development of the project is underway. The Development Plan is being implemented and on schedule for injection.

Active Injection—The project is currently injecting and safely storing CO_2.

It is likely that a framework similar to the PRMS classification for Reserves will be used. However,due to a lack of clear understanding of attributes that will be required to establish CO_2 geologic storage commerciality, a discussion of Proved, Probable, and Possible Storage Capacity for this guideline document is considered too speculative. Nevertheless, additional details on Storage Capacity is available (Frailey and Finley, 2009; Frailey, Finley, and Hickman, 2006).

6.2.4 SUMMARY

With a standardized classification system, project status could be compared consistently between projects throughout the world with a common understanding of the level of detail in the evaluations completed to achieve each project status. This proposed classification system is similar to the petroleum classification system that was developed over decades of active oil production. It is anticipated that a storage resource classification system will evolve into a more robust framework as the CCS industry itself matures and several commercial projects are started.

Due to the infancy of carbon storage, there are some caveats to the proposed classification system. The structural foundation can be developed into classes and sub-classes with general definitions. However, at present, completing the definitions and constructing guidelines for Contingent Storage Resources and Storage Capacity is premature. This level of detail will evolve with experience as commerciality is further defined by the commodity price of CO_2, value for stored CO_2 in pore space, and established "cost of doing business" expenses for power plant operators and other industries involved in CCS are determined. Regardless of these caveats, development of a geologic storage resource classification system is necessary to bring standardization to worldwide geologic storage assessments similar to the standardization evident throughout the petroleum industry.

7.0 SUMMARY AND CONCLUSIONS

This BPM offers best practice guidelines for Site Screening, Site Selection, and Site Characterization in geologic storage projects. The guidelines and approaches presented here are based on lessons learned through the RCSP Initiative, and this 2017 Revised Edition incorporates new findings from the RCSPs' Development Phase field projects. This manual is one of 5 BPMs, which together provide an integrated approach to carrying out geologic storage projects, from inception to completion.

The CO_2 Storage Resource Classification System, which is based on the Petroleum Resources Management System, serves as a framework for evaluating and developing sites for geologic storage. The classification is project based, with each project classified according to its maturity status or its likelihood of advancing to commercial storage. Site Screening, Site Selection, and Site Characterization activities described in this BPM fall under the Prospective Storage Resource class or category in the CO_2 Storage Resource Classification System .

Each site evaluation stage is focused on a particular sub-class in the CO_2 Storage Resource Classification System. Site Screening is focused on evaluation of large areas called Potential Sub-Regions; Site Selection is focused on evaluation of Selected Areas; and Site Characterization is focused on evaluation of Potential Sites for geologic storage.

During Site Screening, Potential Sub-Regions are evaluated to identify Selected Areas most suitable for geologic storage. Site Screening activities utilize existing data and readily available resources, including datasets available from state geological surveys, groundwater management districts, oil and gas commissions, and natural resource agencies. The highest-ranking Selected Areas advance to Site Selection for more detailed characterization.

The purpose of Site Selection is to evaluate Selected Areas and develop a list of Potential Sites suitable for Site Characterization. This stage includes evaluation of technical and nontechnical components, including subsurface geologic data, regulatory requirements, model data, site data, and social data. Prior to initiating analyses of Selected Areas, a multi-disciplinary team defines the analyses to be conducted for each component. Site Selection concludes, in successful cases, with one or more Potential Sites being elevated to the Site Characterization stage.

The purpose of Site Characterization is to systematically scrutinize each Potential Site to define its storage-related attributes in much greater detail and determine whether it should be ranked as a Qualified Site. As with Site Selection, Site Characterization requires a team of experts to plan all technical and nontechnical components to be analyzed. The process is generally divided into two stages: Initial Characterization and Detailed Characterization. Activities and analyses that use existing data and information are considered part of Initial Characterization, while activities that require acquisition of new and additional data are considered part of Detailed Characterization. Once a site has achieved rank as a Qualified Site, its storage resources are classified as Contingent Storage Resources, and it is considered ready for development.

Concepts and terminology used to describe geologic storage technology are evolving, as the state of the art advances and more field projects approach commercially viability. A concept that is currently emerging is that of a "storage complex." A storage complex includes both reservoir and confining zone—addressing the fact that one is of little value without the other. A storage complex may include rocks below, as well as above, the reservoir, and it may incorporate multiple stacked reservoirs within a formation. Such concepts help to emphasize the need for greater integration of data and analyses involved in Site Screening, Site Selection, and Site Characterization for geologic storage projects.

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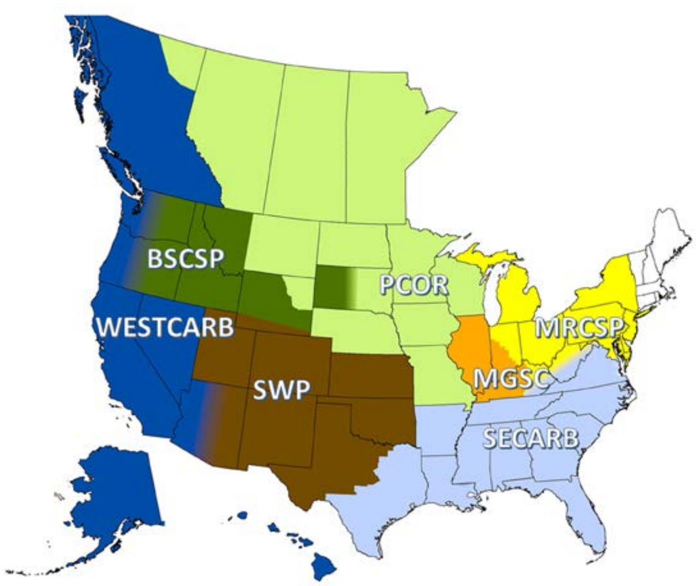
APPENDIX 1—RCSP INITIATIVE

In 2003, the DOE launched the RCSP Initiative, by establishing a network of seven RCSPs distributed across the U.S. The overarching objective of this national initiative is to develop the knowledge base, infrastructure, and technology needed to achieve large-scale storage of CO_2 in geologic reservoirs. The RCSPs contribute to this goal through Characterization, Validation, and Development Phase projects in their respective geographic regions.

The seven partnerships are:

- Big Sky Carbon Sequestration Partnership – http://www.bigskyco2.org
- Midwest Geological Sequestration Consortium – http://www.sequestration.org
- Midwest Regional Carbon Storage Partnership – http://www.mrcsp.org
- Plains CO_2 Reduction Partnership – http://www.undeerc.org/pcor
- Southeast Regional Carbon Sequestration Partnership – http://www.secarbon.org
- Southwest Regional Partnership on Carbon Sequestration – http://www.southwestcarbonpartnership.org
- West Coast Regional Carbon Storage Partnership – http://www.westcarb.org



Characterization Phase Projects: The RCSP's Characterization Phase projects began in 2003. These projects focused on collecting data on CO_2 sources and sinks and developing the resources to enable CO_2 storage testing in the field. By the end of this phase, each partnership had succeeded in establishing its own regional network of organizations and individuals working to develop the foundations for CO_2 storage deployment. Characterization Phase projects culminated in the development of a standard, consistent methodology for estimating geologic storage resource, which has been applied in a series of widely acclaimed Carbon Storage Atlases for the United States and portions of Canada.[3]

Validation Phase Projects: Validation Phase projects began in 2005, with a shift in focus to small-scale field projects to validate the most promising regional storage opportunities. Nineteen small-scale field projects were successfully completed, resulting in more than 1 million metric tons of CO_2 safely stored and monitored. Eight projects were carried out in depleted oil and gas fields, 5 in unmineable coal seams, 5 in clastic and carbonate saline formations, and 1 in basalt. These small-scale tests provide the foundation for larger volume, Development Phase field projects.

Development Phase Field Projects: The Development Phase projects of the RCSP Initiative began in 2008, with large-scale field projects in different geologic settings (Figure 1.1; Table 1.1). The aim of these projects is to confirm that CO_2 capture, transportation, injection, and storage can be achieved safely, permanently, and economically. Results will provide a more thorough understanding of plume movement and permanent storage of CO_2 in a variety of geologic storage formations. Experience and knowledge gained from these projects will also help support regulatory development and commercial deployment of geologic storage. The formations being tested are considered regionally significant and are expected to have the potential to store hundreds of years of CO_2 from stationary source emissions. As of September, 2016, nearly 10 million metric tons of CO_2 have been stored in geologic formations via large-scale field projects being developed by the RCSPs.

NATCARB Atlas: Additional information on the large-scale Development Phase field projects can be found in the *DOE/FE/NETL Carbon Storage Atlas, Fifth Edition (2015)*.

[3] See: http://www.netl.doe.gov/research/coal/carbon-storage/natcarb-atlas

APPENDIX 2—PIPELINE REGULATORY ISSUES

Legislation on CCS has been more focused on the capture and storage of CO_2 than on its transportation, which reflects a perception that transporting CO_2 via pipelines does not present a significant barrier to implementing large-scale CCS and site selection. Even though regional CO_2 pipeline networks already operate in the United States for CO_2-EOR, developing a more expansive national CO_2 pipeline network for CCS will yield new regulatory and economic challenges. There are important unanswered questions about pipeline network requirements, economic regulation, utility cost recovery, regulatory classification of CO_2 itself, and pipeline safety (Marston et al, 2015).

The regulatory framework for siting and operating CO_2 pipelines has developed entirely within the context of their function of supplying a commodity to enhance the recovery of natural resources (CO_2-EOR). An organization wishing to construct a CO_2 pipeline has to obtain an ROW and negotiate with landowners for permission to site the pipeline. Since the responsibility for maximizing resource recovery is a state function, siting authority is held at the state government level. Most states with CO_2-EOR experience have passed legislation allowing CO_2-EOR pipeline operators to use eminent domain to obtain ROW. Since CO_2 injection solely for storage is not related to maximizing resource recovery, only two states (Texas and North Dakota) have laws in place that would apply "common carrier" authority for eminent domain regardless of the destination of the CO_2 (EOR, saline storage, etc). If a major multi-state CCS pipeline backbone is to be constructed, expansion of Federal authority for interstate CO_2 pipelines will be required. The legal process to obtain ROW in these projects is not clear.

The statutory framework for CO_2-EOR pipeline safety regulation now resides at the Federal Department of Transportation under the Pipeline and Hazardous Materials Safety Administration (PHMSA). Interstate pipelines are regulated by PMHSA, while intrastate pipelines are under state regulations as long as their safety standards are as stringent as the Federal regulations.

There are at least three points of conflict, which need to be addressed, between current CO_2 emission reduction policy and present-day pipeline regulations:

1. Carbon dioxide for storage is not "resource extraction," so mineral recovery laws give access to the subsurface solely for extraction of minerals (including oil). Consequently, none of the current state siting rules apply.

2. Subpart RR of the EPA greenhouse gas (GHG) reporting rules for the use of anthropogenic CO_2 in EOR operations could place requirements on EOR operators to obtain prior approval for "monitoring, reporting and verification" plans for each and every injection well. Since these plans are subject to EPA's formal litigation rules, the end result could be several years of delay for each and every new well in the field. This would most likely preclude the use of anthropogenic CO_2 for CO_2-EOR.

3. Capacity apportionment practices that are required for most common carrier pipelines could force CO_2 sources to vent CO_2 in violation of their GHG emission-reduction requirements.

Storing anthropogenic CO_2, even in an EOR setting, does not fit neatly within present-day regulatory regimes. Any new CCS pipeline will need active engagement of Federal, state, and local agencies to pursue resolution to the many issues.

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